NUTRIENT DYNAMICS IN MIOMBO WOODLANDS IN ZIMBABWE

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Abstract

Miombo woodlands are tropical savanna formations dominated by genera *Brachystegia*, *Julbernardia* and *Isoberlinia* and are widespread in central and southern Africa. These woodlands are an important resource providing among other things, grazing and browse for livestock and wildlife, medicines for local people, food like mushroom and honey and timber for building and fuel. Understanding the structural and functional characteristics of miombo ecosystems and the factors affecting and controlling production is therefore important, both for their significance in understanding the environment and also for their value to local communities. In addition to soil moisture, herbivory and fire, soil nutrients are known to be an important determinant of savanna ecosystems.

Nutrient dynamics have been studied at two Zimbabwean sites providing a range of representative miombo environments – the Henderson Research Station near Mazowe and the Mukuvisi Woodlands in Harare. The aim of the research has been to assess the major inputs and outputs of macronutrient nutrients (principally N, P, K, Ca and Mg) in miombo woodlands and to determine the effects of fire on nutrient cycling.

The quantities of nutrients added in rainfall and throughfall were measured during the 1999/2000 and 2000/2001 rainy seasons. Additions of mineral N in rainfall were 14.7 and 7.4 kg/ha/yr at the Mukuvisi Woodlands experimental sites for the 1999/2000 and 2000/2001 rainy seasons respectively. Mineral N added at the Henderson Research Station experimental sites was 12.3 and 5.7 kg/ha/yr for the 1999/2000 and 2000/2001 rainy seasons respectively. Cation input in rainfall was very low at Henderson compared to Mukuvisi, a result which can be explained by the high level of pollution in and around Harare. The amount of cations added during the 2000/2001 ranged from 0.8 to 7.8 kg/ha/yr and 0.2 to 1.2 kg/ha/yr for Mukuvisi Woodlands and Henderson Research Station experimental sites respectively, with K being the highest added in rainfall at both study areas. Nutrients were altered significantly by the canopy. Most of the N was absorbed and/or adsorbed whereas cations were significantly increased. Stem flow was measured only at Henderson Research Station sites and nutrient additions were very low (<0.3 kg/ha/yr) compared to throughfall.

Dominant miombo tree species were found to conserve nutrients by re-absorbing them from senescing leaves. Phosphorus had the largest percentage withdrawn for all the dominant tree species and this ranged from 48 to 75 % of the total P in mature leaves (in November 1999). Total N, K and Mg withdrawn ranged from 22 to 33, 22 to 31 and 12 to 21 % respectively. Litterfall at the study sites ranged from 2.20 to 4.44 t/ha/yr. Litterfall (<2 cm) is the largest nutrient cycling pathway in miombo woodlands, transferring between 36.6 to 65.2 kg N/ha/yr; 5.5 to 10.2 kg P/ha/yr; 15.3 to 26.7 kg K/ha/yr; 28.7 to 53.8 kg Ca/ha/yr; 4.9 to 8.6 kg Mg/ha/yr and 1.2 to 2.1 kg Na/ha/yr to the woodland floor. Litter decomposition was faster at the Henderson sites where there is evidence of high termite activity. K and Na were released fastest from decomposing litter compared to other nutrients.

Nutrients leached from miombo soils were in the order K (1.24-2.52 kg/ha/yr) > NO_3^--N (1.11-2.30 kg/ha/yr) > Ca (0.82-1.49 kg/ha/yr) > NH_4^+-N (0.39-0.83 kg/ha/yr) > Na (0.28-0.54 kg/ha/yr) ≈ Mg (0.32-0.52 kg/ha/yr). Potassium was the most easily leached nutrient from litter and it was also found to be the highest cation in leachate collected from 100 cm depth. Losses of N in the form of N_2O were also measured and were found to range from 0.29 to 0.60 kg/ha/yr and 0.27 to 0.62 kg/ha/yr at Mukuvisi Woodlands and Henderson Research Station experimental areas respectively. Compared to nutrient additions, losses through this pathway are low. Early burning resulted in loss of nutrients N, P, Ca, Mg, K and Na from herbaceous vegetation and, from litter, only N was lost in significant amounts.

From the study it can be concluded that rainfall is an important nutrient input. Throughfall also contributes substantially to nutrients added to soils in miombo woodlands especially bases. The results from this study seem to indicate that miombo woodlands cycle nutrients efficiently with minimum losses. The internal nutrient cycling comprising mainly litterfall is able to re-circulate the largest proportion of nutrients. Losses through gaseous N_2O emissions and leaching losses relative to the sum of throughfall and stem flow were found to be low. Fire resulted in some nutrient losses confirming the hypothesis that burning miombo woodlands results in significant loss of nutrients.

Declaration

I hereby declare that this thesis is my own composition and the results presented were generated by myself except where clearly and specifically acknowledged. This work has not been presented in any previous application for a higher degree.

Menas Wuta

Dedication

This thesis is dedicated to my dear wife Getrude and our children Fadzai, Gamuchirai, Tariro and Mazvita.

"I can do everything through Him who gives me strength" – Philippians 4:13

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ABBREVIATIONS AND GLOSSARY OF TECHNICAL TERMS USED IN THE THESIS

Hen-Low - Henderson woodland experimental area on a lower slope catenary position

Hen-Mid - Henderson woodland experimental area on a middle slope catenary position

Hen-Up - Henderson woodland experimental area on an upper slope catenary position

Muk-Burn - Mukuvisi woodland experimental area subjected to an annual early burn

Muk-Def - Mukuvisi experimental area deforested and subjected to an annual early burn

Muk-Grass - Mukuvisi grassland experimental area inside the protected and fenced area

Muk-Prot - Mukuvisi woodland experimental area inside the protected and fenced area

BB – Before burning

AB – After burning

PAN – Plant available nutrients

PAM – Plant available moisture

Dambo/vlei – low lying area which is periodically waterlogged and lies close to the base level and watertable

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Figure 9.5. Summary diagram of nutrient cycling in Hen-Low miombo woodland (the lower section of the catena at Henderson) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Leaching and stem flow measurements were carried out in this experimental area. Leaching measurements presented were carried out at a depth of 100 cm. 221

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1. INTRODUCTION

1.1 IMPORTANCE OF MIOMBO WOODLANDS

Savanna formations are the most widespread vegetation type found in tropical Africa (White, 1983) and they form a major biome in which both grasses and woody plants are major components (Huntley and Walker, 1982, Bourliere and Hardley, 1983; Walker, 1985). Worldwide, savannas are found in Africa, America, Australia and Asia, four diverse continents. The diversity of location has led to various definitions and descriptions of savannas on the basis of climate and vegetation (Mistry, 2000). The original definition of savannas included only tropical grasslands without trees but over the years the definition has been extended to include trees (Bourliere and Hardley, 1983; Mistry, 2000). Frost *et al.* (1986) described savanna as *"tropical and some near-tropical ecosystems characterised by a continuous herbaceous cover consisting mostly of heliophilous C4 grasses and sedges that show clear seasonality related to water stress. Within these ecosystems woody shrub and tree species do occur but seldom form a continuous cover similar to that of the grassy layer."* Miombo is a woodland-dominated end of the spectrum of savanna formations and is the most widespread savanna woodland in southern and central Africa. In this region miombo woodlands extend from Tanzania and southern Democratic Republic of Congo in the north to Zimbabwe in the south, and across the continent from Angola, through Zambia to Malawi and Mozambique (Campbell *et al.*, 1996). In the whole of Africa it is estimated to cover more than 2.7 million km^2 (Millington *et al.* 1994). In Zimbabwe, miombo woodlands cover about 50 % of the country and the distribution of vegetation physiognomic types in Zimbabwe is shown in Figure 1.1.

Brachystegia, *Julbernardia* and/or *Isoberlinia* are the dominant genera in miombo woodlands (White 1983). These genera belong to the legume family, *Fabaceae*, subfamily *Caesalpinioideae*. Undisturbed and mature miombo form partly closed deciduous woodlands with trees that are 10-20 m high. Like most tropical savannas they occur on old and weathered surfaces, where there are nutrient poor soils, in a unimodal

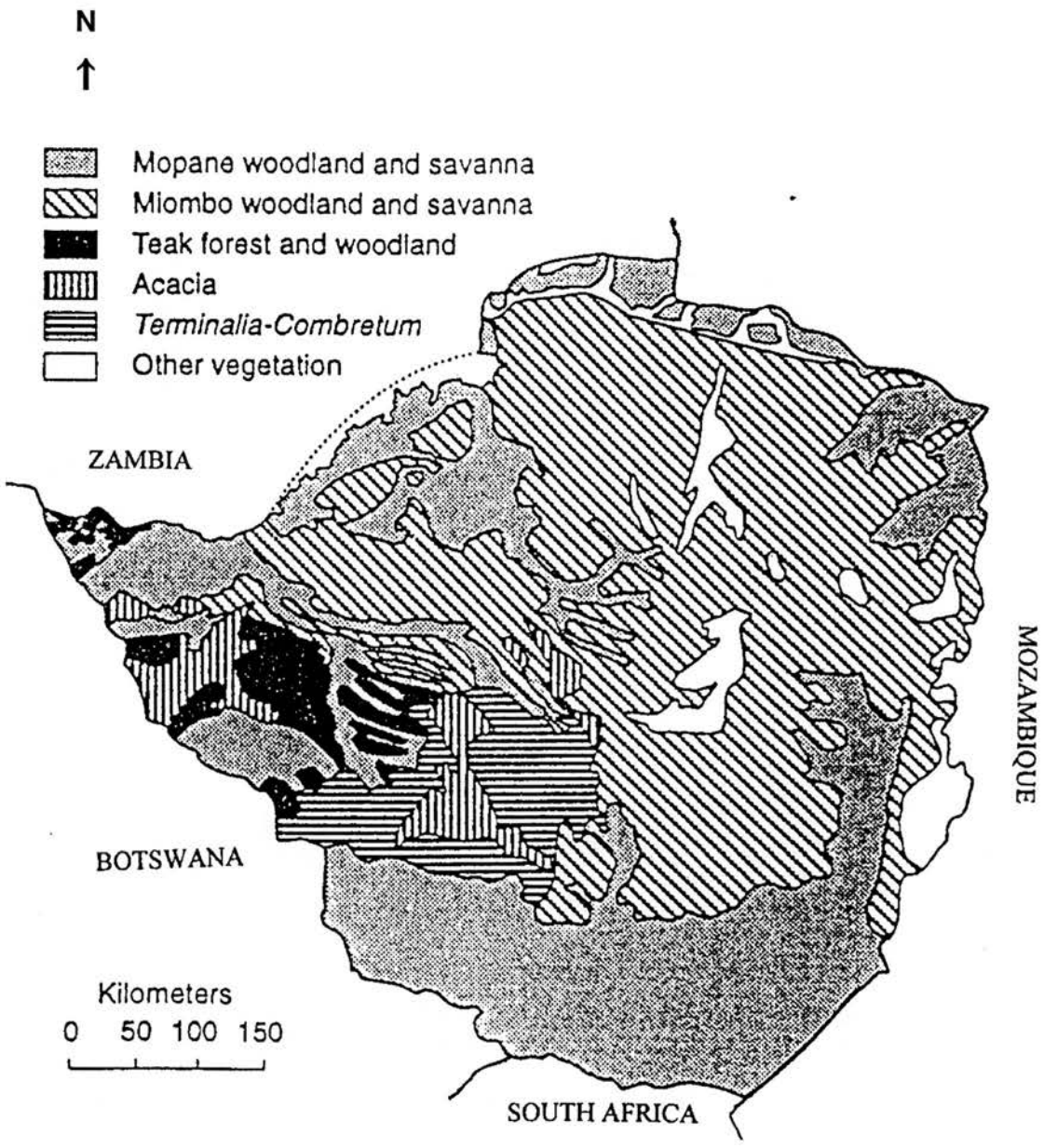


Figure 1.1 Map of vegetation distribution in Zimbabwe (Rattray and Wild, 1961).

rainfall zone (Campbell *et al.*, 1996). The understorey is made up of discontinuous shrubs and sparse but continuous herbaceous plants. The herbaceous layer is made up of forbs, small sedges and heliophytic C4 grasses with the dominant belonging to the family, *Andropogoneae* (Frost, 1996). Though vegetation is the most conspicuous feature, miombo woodlands are also associated with many wild animals, which exert their influence on the systems in different ways, such as herbivory. The abundance and distribution of animal and vegetation species in the woodlands is continuously affected by human activities, which derive products and services from the system (Morris, 1970; Clarke *et al.*, 1996).

Miombo is an important resource and a source of livelihood to a large human population (Lawton 1982; Campbell *et al.*, 1991: Bradley and Dewees, 1993; Clarke *et al.*, 1996). Large miombo areas make up national game parks and safari areas, which are important for tourism in a number of southern African countries. Local communities depend on products from these woodlands. Products derived from miombo include medicines, food, for example, edible caterpillars, game meat, honey, wild fruits and mushrooms, timber for building and fuel. Most of these products are not only used in rural areas but are also very important in urban areas where many of them are marketed, e.g., firewood and mushrooms. Miombo woodlands also provide grazing and browse for livestock. In some smallholder crop and livestock farming systems in Zimbabwe, where farmers are resource poor, miombo litter is used as a soil organic amendment, for example in Wedza Communal area (Wuta and Nyamugafata, unpublished), in Shurugwi Communal Area (McGregor, 1995) and Masvingo (Nyathi and Campbell, 1994). The woodlands also have social values related to spiritual and religious needs. In most communities in the miombo zone, people believe that some woodlands are guarded by ancestral spirits (Clarke *et al.*, 1996) and some trees or parts of the woodlands are holy and therefore important religious ritual sites.

In spite of the role of miombo in meeting human needs in Zimbabwe and other parts of Africa, there is extensive degradation of these woodlands due to changing patterns in land use and unsustainable harvesting of some miombo woodlands products particularly

fuel (Clarke *et al.*, 1996). Reductions in the area of uncultivated woodlands reduce the availability of fuel wood, construction material, and non-timber forest products; diminish the area of communal grazing land; and adversely affect the ecological services provided by the trees. Conversion to permanently cropped land and/or degradation, in the absence of intensive soil management can lead to reductions in soil organic matter, nutrient depletion, extreme desiccation and soil erosion (Elwell, 1983 & 1985). Use of goods and services from this natural resource must be optimized but use must be sustainable. To be able to achieve this, there is need to understand better the structural and functional characteristics of miombo ecosystems and the factors controlling production, including human activities, that is, land use practices. Some of these factors that need to be investigated range from soil nutrients, soil moisture and frost to the effect of tsetse fly, large mammals and fire. The present research focuses on nutrients cycling in miombo woodlands.

1.2 ENVIRONMENTAL CONTEXT OF MIOMBO WOODLANDS

Climate of the miombo region is strongly seasonal with cool winters and warm summers. The region receives most of its rainfall during the summer for a period of 5 to 7 months (Frost, 1996) and mean annual precipitation ranges from about 650 to 1400 mm (Campbell *et al.*, 1996). The dry period can last for between 2 and 9 months (Mistry, 2000). On the basis of rainfall, White (1983) divided the woodlands into dry miombo woodlands receiving <1000 mm per annum and wet miombo woodlands that receive > 1000 mm per annum.

Miombo woodlands are found on flat to undulating terrain classified as African and post-African planation surfaces (Cole, 1986). The undulating terrain has catenary sequences which strongly influence distribution of miombo species, the woodlands occupying the slopes and giving way at lower catenary positions to species tolerant to poor drainage conditions. In more fertile lower slope positions with more favourable moisture conditions, open *Acacia*-dominated woodlands are present (Campbell *et al.*, 1996).

Soils are generally well drained and infertile. They are classified in the USDA Soil Taxonomy (1990), predominantly as alfisols, ultisols and oxisols (Frost, 1996). In the Zimbabwean soil classification, soils belong to the Kaolinitic order (Thompson and Purves, 1978; Nyamapfene, 1991). Soils have low cation exchange capacities (2 - 18 cmol (+)/kg), low total exchangeable bases (1-15 cmol(+)/kg), high acidity (pH 4-6 in $CaC1_2$), low organic matter contents (0.3-3.8% in the A-horizon), low available phosphorus (9-19 mg/kg), and a dominance of low activity clays and sesquioxides (Watson 1964; Webster, 1965; Trapnell *et al.*, 1976; Young, 1976; Purves *et al.* 1981; Celander, 1983; Stromgaard, 1984; Lenvain and Pauwelyn, 1988; Mapiki, 1988; Anderson *et al.*, 1993). It is ecologically important to find out how the dominant leguminous miombo species, *Julbernardia globiflora* and *Brachystegia spiciformis* survive and maintain the fertility of nutrient-depleted soils and yet do not have root-bacteria symbiotic N-fixing association.

1.3 MIOMBO SOILS NUTRIENT RESEARCH

Miombo woodland soil and nutrient research has been limited to litter chemical composition and laboratory decomposition (Mtambanengwe and Kirchmann, 1995), effect of termites on woodland soil properties (Trapnell *et al.*, 1976, Jones, 1990) and foliage chemical composition (Ernst, 1975; Campbell *et al.*, 1988; King and Campbell, 1994; Nyathi and Campbell, 1994). The research thrust of most of this work has been mainly towards agriculture, for example, miombo leaf prunings and litter as a source of nutrients for crops (Nyathi and Campbell, 1994; Musvoto and Campbell, 1995; Musvoto *et al.*, 2000). Though useful, information available is fragmented and does not clarify nutrient geochemical cycles in miombo woodland ecosystems. There is limited information on nutrient cycling in miombo woodlands and in tropical savannas in general (Malaisse *et al.*, 1975; Frost, 1985a). To understand nutrient dynamics and the extent of nutrient limitation there is need for field monitoring and appropriately designed field experiments (Jaramillo and Sandford, 1985). Frost (1996) notes that no such work has been conducted in miombo woodlands.

Miombo woodlands are notable among dry tropical woodlands and forests for the number of tree species having ectomycorrhizae (ECM) rather than vesicular-arbuscular mycorrhizae (VAM) associations (Högberg, 1982; 1986 & 1992; Högberg and Piearce, 1986; Högberg and Alexander, 1995). These associations are believed to enable plants to take up nutrients from the soil and also directly from plant litter and are therefore important in nutrient cycling. Their role in N cycling in miombo woodlands needs to be determined. There is no documentary evidence of similar work done in Zimbabwe.

Water, fire, herbivory and soil nutrients have been recognised as the major ecological determinants of savanna woodlands (Scholes and Walker, 1993; Campbell *et al.*, 1996; Frost, 1996). Besides these factors, Walker (1985) recognised the role of stochastic events, which can have a significant effect on the physiognomic and floristic structure of savanna communities, like severe drought or incidence of periodic catastrophic storms. Soil moisture and soil nutrients have, however, been identified as the major fixed primary determinants of savanna ecosystems whilst fire and herbivory are variable determinants (Bell, 1982; Walker, 1985). The effect and role of these determinants especially nutrients need to be investigated in the field so as to understand miombo ecosystems.

A lot of gaps exist in our knowledge of miombo woodland functioning and maintenance. This study focusses on the ecological determinant, nutrients, in miombo woodlands. A study of nutrient cycling will provide valuable information on ecosystem function and fertility maintenance and may offer useful data on the effect of current management and land use practices.

1.4 AIMS OF THE RESEARCH

This study seeks to understand macronutrient N, P, K, Ca and Mg dynamics in miombo woodlands. It aims at answering a series of questions about the major **inputs** and **outputs of these nutrients** and **their movement within** (internal cycling) the woodlands (Figure 1.2). Such questions will lead to an understanding of nutrient

dynamics in miombo woodlands. Research questions that needed to be addressed can be divided into three categories namely: nutrient input, output and internal cycling.

1.4.1. Nutrient inputs

The major potential sources of nutrients are incident precipitation, throughfall (i.e. canopy leaching or precipitation falling through the tree canopy) and stem flow. The question that needs to be addressed is:

- How much and in what form are nutrients added to the system from these sources?

1.4.2. Internal cycling of nutrients

Nutrients within miombo woodlands are always moving from one part of the system to another. A number of questions about the internal cycling of nutrients need to be addressed and they are listed below.

- How much of the nutrients are taken up in leaves from leaf development up to senescence?
- How much of the nutrients accumulate in woody plant parts of the dominant miombo tree species?
- How much of the nutrients are transferred to the woodland floor as litter fall?
- What nutrient changes occur during litter decomposition?
- What is the effect of fire on vegetation structure and composition and nutrient dynamics?

1.4.3. Nutrient outputs

Like all ecosystems, there are nutrient losses that occur from the woodlands. There is need to understand:

- How much of the nutrient N is lost from miombo woodlands through gaseous emissions?
- How much of the nutrients are lost from miombo woodlands through leaching?
- How much of the nutrients are lost through woodland fires?

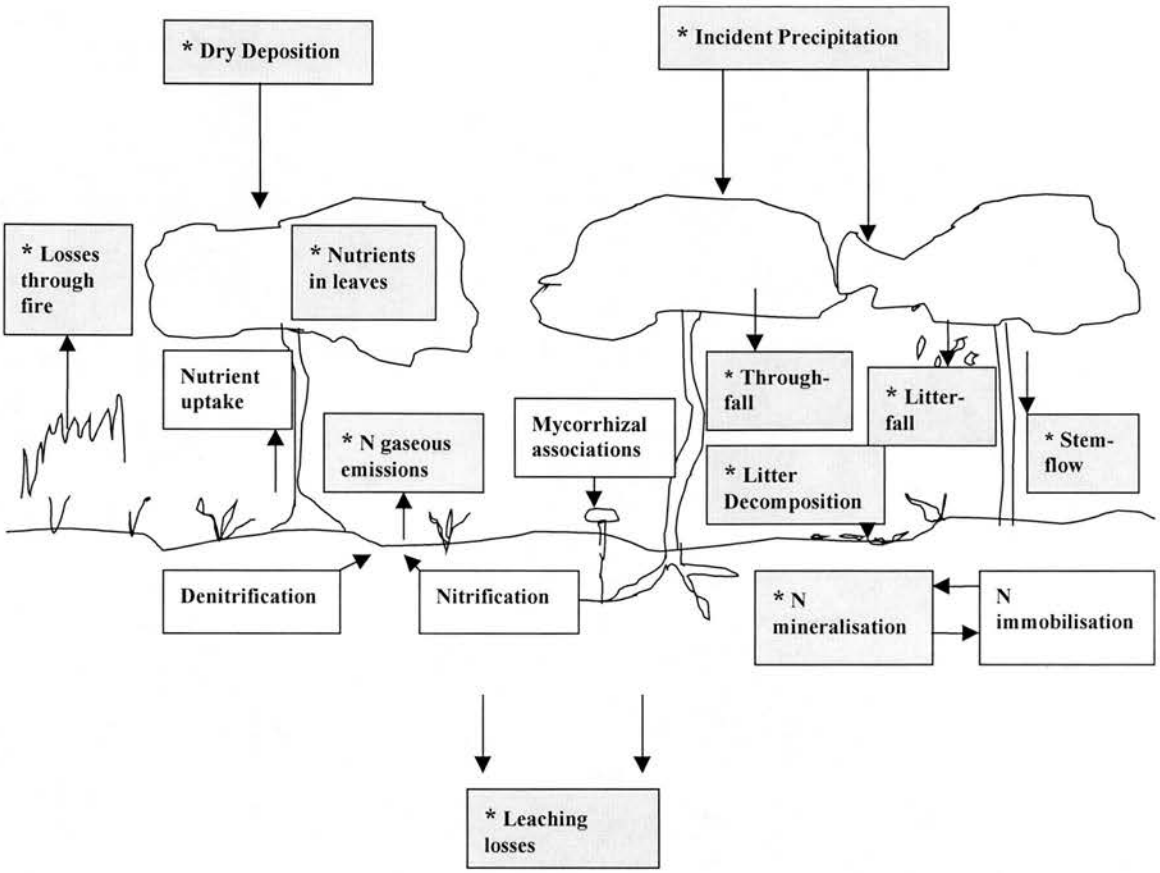


Figure 1.2 Nutrient inputs, outputs and internal cycling in miombo woodlands. The compartments measured in this study are shaded and marked with an asterisk (*).

In order to answer these questions a series of measurements and experiments were carried out in selected miombo woodlands. It was hypothesized that miombo woodlands recycle nutrients efficiently without significant losses from the system but that fire has the effect of increasing nutrient losses from the system.

1.5 THESIS STRUCTURE

Chapter 1 provides an introduction to the thesis. Chapter 2 gives an outline of the general materials and methods used. The third chapter gives vegetation characteristics of the study sites. Chapter 4 explores the nutrient inputs from rainfall and how these inputs are affected by the canopy and by tree stems. Chapter 5 examines internal cycling of nutrients through litter fall. In this chapter changes in nutrient contents of leaves from leaf development to senescence are discussed. Litter fall patterns over the growing season and their nutrient contents and litter decomposition at the different sites are also compared. Chapter 6 discusses the effect of fire on miombo woodland nutrient dynamics. Losses of nutrients from the miombo ecosystems through leaching are covered in chapter 7 whilst losses of N as nitrous oxide gaseous emissions are covered in chapter 8. The last chapter, Chapter 9 discusses the major findings of this study highlighting the implications to miombo woodlands and in conclusion pointing out areas for further research.

2. GENERAL MATERIALS AND METHODS

2.1 STUDY SITES

2.1.1 Mukuvisi Woodlands

The Mukuvisi Woodlands are situated about 5 km east of the Harare city centre and represent one of a few woodlands still remaining within the city (Figure 2.1). It is located between 17° 45′ and 17° 55′ south latitudes and 31° 5′ and 31° 10′ east longitudes. The woodland is bordered both in the north and south by streams and about 265 ha in extent. It is divided into two sections, a protected area where a few wild animals are kept and is enclosed by an electric fence and secondly a public walking area. The protected area takes up about two thirds of the Woodland's total area and is almost equally divided into a miombo woodland area and a grassland area which extends towards the stream in the north. The public walking area is in the south and is outside the electric fence. The area outside the fence has been burnt every year, and has been since mid 1980's, in order to protect the fenced area where the animals are shielded from fire as much as possible. Various animal species are kept in the woodland and these include zebra, impala, wildebeest, eland and giraffe. The burnt section is also a miombo woodland area with the exception of the eastern edge that has been deforested. The deforested area, which is also burnt annually, is approximately 50 m wide and runs from north to south along the eastern side of the woodland burnt area. The deforested area is characterised by grass and occasional shrubs of about 1 m and less high. Trees have been cleared from this area because there is a high voltage electricity power line running through. At Mukuvisi Woodlands, the experiments included areas within the protected woodland area (Muk-Prot), the protected grassland area (Muk-Grass), the burnt woodland area (Muk-Burn) and the burnt deforested area (Muk-Def).

The Harare region, in which the Mukuvisi Woodlands lie, reaches an altitude of between 1300-1500 m above sea level. The wet summer season is from November to

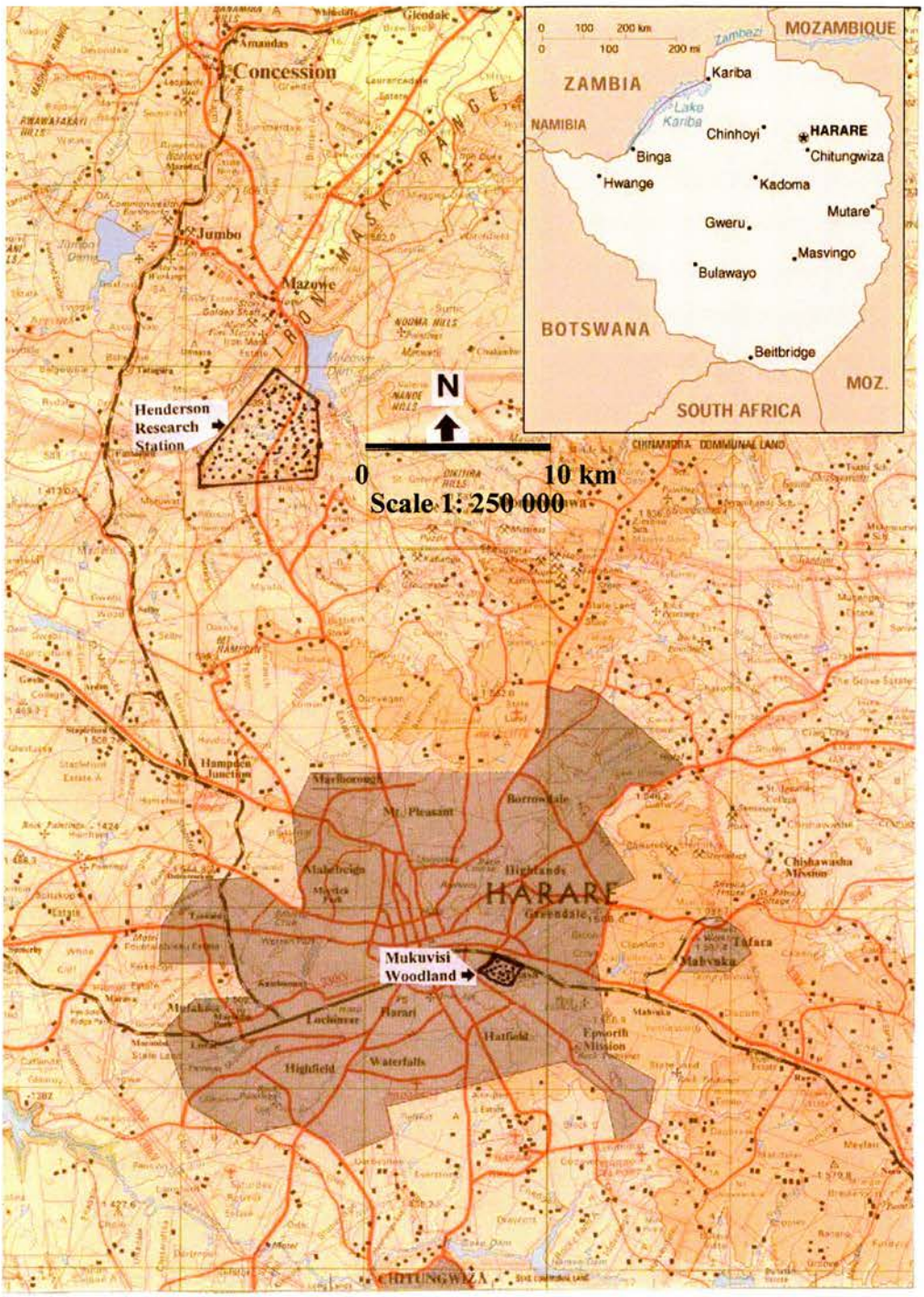


Figure 2.1. Map at a scale of 1cm: 2.5 km showing location of Mukuvisi Woodland in Harare and Henderson Research Station near Mazowe. Inset map of Zimbabwe at a scale of 1 cm : 100 km showing the location of Harare where the Mukuvisi Woodland is located. (Source: Surveyor General, Zimbabwe, 1992).

March and mean annual rainfall is about 840 mm. The mean annual temperature is in the range of 15-20 °C. Warm to hot temperatures of between 26 – 35 °C are recorded from September to October. The cold dry, winter season is from April to August and has maximum temperatures of 16-20 °C with occasional night-time ground frost.

Mukuvisi Woodland is underlain by coarse-grained granite (Baldock, 1991) which gives rise to coarse textured sandy soils. The soils are classified at the great group level in the USDA Soil Taxonomy (Soil Survey Staff, 1998) as Ustipsamments.

2.1.2 Henderson Research Station

The Henderson Research Station is located on a farm near Mazowe about 35 km north of Harare (Figure 2.1). It is situated between 17° 30′ and 17° 40′ south latitudes and 30° 55′ and 31° 5′ east longitude. The research station is one of the many satellite research stations of the Department of Research and Specialist Services, Ministry of Lands, Agriculture and Rural Resettlement of the Government of Zimbabwe. It specialises in livestock, weeds, pasture, fish and poultry research.

It is underlain by argillaceous meta-sediments that give rise to clay-rich soils with a high silt content. It is in a valley surrounded by a range of hills and has an altitude of about 1200 m above sea level. This area lies between 100 and 300 m lower in altitude compared to Harare. The mean annual rainfall is slightly lower than Harare and is about 760 mm. Mean annual temperature ranges from 16 °C to 21 °C. Warm to hot temperatures of between 25 – 37 °C are recorded from September to October.

The station has a large area under natural miombo woodland, the bulk of which is close to or on the hills. Some of the woodland and pasture areas are protected from fire by fireguards. The fireguards are strips of areas cleared of trees and grass vegetation of at least 10 m width. Clearing of fireguards is done annually through controlled burning between May and July.

A woodland portion of about 10 ha in extent was selected from the section protected from fire. This area has a catenal variation of soils with three distinct topographic sections, the upper-slope (Hen-Up), mid-slope (Hen-Mid) and the lower-slope (Hen-Low) which lies close to a drainage line. At the Henderson site, the three topographic sections were taken as the experiment areas. Soil profile descriptions in appendix 3, show the different soils in the different topographic positions. The soils are classified at the great group level in the USDA Soil Taxonomy (Soil Survey Staff, 1998) as Haplustalfs.

2.2. SAMPLING AND LABORATORY ANALYSIS

2.2.1. Site characterisation

The study sites were characterised by describing the vegetation, that is, grass and tree species and soils. A vegetation survey was carried out using sample areas for the trees and quadrats for grass and herbaceous plants. The sample areas were located along transects.

Soil surveys were carried out to identify soils in the study areas. Representative soil pits were dug and fully described at each of the study sites according to Bennet (1985). In the Mukuvisi Woodlands, 4 representative pits were dug, one each in the protected woodland area, protected grassland area, burnt woodland area and the burnt deforested area (Appendix 3). At the Henderson Research Station site, one pit was dug in each of the topographic positions, namely upperslope, mid-slope and lowerslope making a total of 3 soil pits (Appendix 3). Soil samples were collected from genetic horizons identified in the field for laboratory analysis. Soil texture was determined using sieves for the sand fraction (2-0.02 mm) (Bennet, 1985) and the hydrometer method (Bouyoucos, 1962 and Okalebo *et al*, 1993) for the silt (0.02-0.002 mm) and clay (<0.002 mm) fractions. Textural classes were assigned using the Zimbabwean texture classification system (Bennet, 1985). Cation exchange capacity of the soils was determined using the ammonium acetate method (Anderson and Ingram, 1993). The exchangeable bases calcium and magnesium, were determined using an atomic absorption

spectrophotometer and potassium and sodium using a flame photometer. The bases were extracted from the soils using ammonium acetate (Anderson and Ingram, 1993). Soil pH was determined using a 1:5 suspension of soil and calcium chloride solution.

2.2.2 Soil sampling and analysis

Soils were sampled from small pits, that is, "mini" pits, approximately, 30 cm square and 40 cm deep were dug along transects at regular 20 m intervals. Soil samples were collected carefully from cleaned opposite sides from depths, 0-3 cm, 3-6 cm, 6-10 cm, 10-20 cm and 20-30 cm. Soils from the same depths from the opposite sides were mixed to make a composite sample. Composite samples were air dried, ground and sieved to pass through a 2 mm sieve. They were then analysed for microbial C and N, total C, N, P, K, Ca and Mg. Duplicate standard soil samples, analysed by a reputable external laboratory were always included in the analyses for use in quality control of the results obtained.

i) Total organic C

Total organic carbon was determined using Nelson and Sommers' (1996) complete wet oxidation method using an excess mixture of concentrated sulphuric acid and aqueous potassium dichromate as an oxidising agent with external heating (Anderson and Ingram, 1993).

Ground soil (<0.15 mm) weighing about 0.5 g was transferred into a digestion tube. Five ml of 1 M potassium dichromate and 7.5 ml concentrated sulphuric acid were added to the soil and digested at 145-155 ^{o}C for 30 minutes. The cooled digest was quantitatively transferred to a 100 ml flask and 0.3 ml ferroin indicator (1.485 g 1,10 ortho-phenanthroline monohydrate in 100 ml 0.025 M ferrous sulphate) was added to the solution. The solution was titrated with 0.2 M ferrous ammonium sulphate solution to a brown colour end point.

Calculation:

$$\% \, Organic \, Carbon = \frac{(Vb - Vs) \; x \; 0.2 \; x \; 0.3}{sample \; weight},$$

where,

Vb = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate reagent blank solution and

Vs = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate sample solution

ii) Microbial C and N

Microbial C and N were determined using the Chloroform Fumigation Method (Horwath and Paul, 1994 and Rice *et al.*, 1996). After 7 days of incubation at 25 °C and 55 % of soil water-holding capacity, microbial biomass carbon (MBC) was determined by the Fumigation Extraction (FE) procedure (Rice *et al.*, 1996), where half of the samples were fumigated with alcohol-free chloroform in a vacuum desiccator for 36 hours. Both the fumigated and non-fumigated samples were extracted with 0.5 M K_2SO_4 (30 ml), filtered and an aliquot (4 ml) was oxidised using 0.066 M $K_2Cr_2O_7$ (1 ml) with concentrated H_2SO_4 (5 ml). Excess $K_2Cr_2O_7$ was determined by back-titration against 0.033 M $Fe(NH_4)_2(SO_4)_2.6H_2O$ with 1,10-phenanthroline-ferrous sulphate as an indicator. Organic carbon (C) was calculated assuming that 1 ml of 0.066 M $K_2Cr_2O_7$ oxidises 1200 μg C (Rice *et al.*, 1996). Differences in C contents in fumigated and non-fumigated samples gave the amounts of MBC. The MBC results were corrected for moisture content, volume of extracting solution and divided by a constant (K_c = 0.35) to correct for the proportion of the microbial C extractable from the soil by this method (Weaver *et al.*, 1994).

Microbial N was determined by Kjeldahl digestion of a 5 ml sample of the extract from fumigated and non-fumigated samples. The solution was steam distilled in the presence of 10 ml of 40 % sodium hydroxide (40 g/100 ml distilled water). The distillate was collected in 50 ml of 2 % boric acid (2 g/100 ml distilled water) with four drops of an indicator. The indicator solution was prepared by mixing in a 100 ml volumetric flask,

0.2 g methyl red and 0.13 g bromocresol green and making to the mark with alcohol. The distillate was titrated with 0.096 M hydrochloric acid using a micro-burette until the indicator changed from green through grey to a definite pink end point (Okalebo *et al.*, 1993). Differences in N contents in fumigated and non-fumigated samples gave the amounts of microbial biomass N.

iii) Total N, P, K, Ca and Mg

Soil samples were acid digested using sulphuric acid and hydrogen peroxide. Selenium oxide was used as a catalyst and lithium sulphate added to raise the boiling point of the mixture (Anderson and Ingram, 1993). This method brings all the nutrients, N, P, K, Ca, and Mg into solution. Total nutrients were therefore determined on solutions from the digests.

The digestion mixture was made up of 350 ml H_2O_2, 0.42 g selenium powder and 14 g lithium sulphate, where 420 ml of concentrated H_2SO_4 (specific gravity - 1.84) was added to the mixture with swirling and cooling. Immediately before analysis samples were oven dried for at least 3 hours at 100°C. 0.5 g sample was digested with 4.4 ml of the digestion mixture by heating gently initially then more strongly for 1.5 hours. The digest was cooled and quantitatively transferred into a 100 ml volumetric flask and made to the mark with distilled water and mixed thoroughly.

Total nitrogen was determined using the Kjeldahl method. A 20 ml aliquot of the digest was taken and mixed with 50 ml of 40 % NaOH (40 g/100 ml distilled water) and steam distilled. The distillate was collected in 50 ml of 2 % boric acid (2 g/100 ml distilled water) with four drops of an indicator. The indicator solution was prepared by mixing in a 100 ml volumetric flask, 0.2 g methyl red and 0.13 g bromocresol green and making to the mark with alcohol. The distillate was titrated with 0.096 M hydrochloric acid using a micro-burette until the indicator changed from green through grey to a definite pink end point. A blank determination was run by digesting reagents without the sample and distilling as above. The blank distillate solution was then titrated with 0.096 M

hydrochloric acid. The blank titre was subtracted from the sample titration to obtain the corrected sample titre, T.

Calculation:

$$\text{Total N (\%)} = \frac{T\,(ml)\ x\ Solution\ volume\ (ml)}{100\ x\ aliquot\ (ml)\ x\ sample\ wght\ (g)}$$

Total P was determined colorimetrically after colour development with an ammonium molybdate and ammonium metavanadate mixed reagent (Okalebo *et al.*, 1993).

Ammonium molybdate (80 g) was dissolved in warm (±50°C) ± 800 ml distilled water. Ammonium metavanadate (2 g) was dissolved in ± 600 ml boiling distilled water, cooled and 600 ml concentrated nitric acid added slowly. Ammonium molybdate solution was added gradually with stirring and the solution was made up to 2 litres with distilled water.

The sample solution, that is, 5 ml was pipetted and 0.2 ml 0.5 % w/v paranitrophenol (0.5 g paranitrophenol in 100 ml distilled water) indicator added. The solution was neutralised with a 6 M ammonia solution until a yellow colour just develops. Dilute 1 M HNO_3 was added dropwise with shaking until the solution was just colourless. Colour was developed by adding 5 ml of the ammonium molybdate/ammonium metavanadate mixed reagent. Standard P solutions with 0, 1, 2, 3, 4, 5 and 10 µg/ml P were made up using KH_2PO_4. To the standard solutions, 5 ml of the ammonium molybdate/ammonium metavanadate mixed reagent was added to develop colour. Absorbances of the sample solutions and the standard solutions were measured using a UV/spectrophotometer at 450 nm wavelength setting. The concentration of P in the sample was then read from the standard curve of absorbance versus P concentration in the standards.

The total bases calcium and magnesium, were determined using an atomic absorption spectrophotometer and potassium and sodium using a flame photometer.

iv) Mineral N - NH_4^+ - N and NO_3^- - N

Mineral N, that is, ammonium-N and nitrate-N, was determined using the method described by Okalebo *et al* (1993). Freshly sampled soil samples (10 g) were shaken with 100 ml 2 M KCl extracting solution for about 1 hour and filtered. It was ensured that the analyses were completed on the day of extraction otherwise samples were refrigerated. The ammonium and nitrate nitrogen were determined using the method outlined by Okalebo *et al*, 1993.

A 10 ml aliquot of the soil extract was distilled after adding approximately 0.2 g MgO. The MgO was first ignited in a muffle furnace for 2 hours at 600-700 ^{o}C, cooled and stored in a tightly stoppered bottle. The distillate was collected in a conical flask with 5 ml boric acid with indicator solution. The amount of ammonium-N was determined by titrating with 0.002 N H_2SO_4 in a microburette to a permanent faint pink colour.

Nitrate nitrogen was determined in the same sample used to determine ammonium nitrate, by adding approximately 0.2 g Devarda's alloy to the sample to reduce nitrate-N to ammonium-N. The sample was distilled again into fresh boric acid in another receiving flask. The amount of nitrate-N was determined by titrating as before with 0.002 N H_2SO_4 in a microburette to a permanent faint pink colour.

The amount of ammonium-N and nitrate-N was corrected on soil oven-dry (105 ^{o}C) basis, as follows:

$$Corrected\ mineral\ N = (amount\ of\ mineral\ N)\left(\frac{weight\ \ of\ oven\ dry\ \ soil}{weight\ \ of\ \ fresh\ \ soil}\right)$$

2.2.3 Analysis of foliar and litter (plant material) samples

Foliar and litter samples were analysed for total N, P, K, Ca, Mg and organic C. Litter samples used in the decomposition experiment were also analysed for initial total lignin,

cellulose, hemicellulose and polyphenols. Duplicate standard plant material samples, analysed by a reputable external laboratory were always included in the analyses for use in quality control of the results obtained.

i) Total N, P, K, Ca and Mg

Foliar or litter samples were acid digested using sulphuric acid and hydrogen peroxide. Selenium oxide was used as a catalyst and lithium sulphate added to raise the boiling point of the mixture (Anderson and Ingram, 1993). The same method which was used for soil samples was used for foliar samples. The method brings all the nutrients, N, P, K, Ca, and Mg into solution. Total nutrients were therefore determined on solutions from the digests.

Before analysis plant material samples were oven dried at 60 ^{o}C for 48 hours. Samples were finely ground and 0.5 g was taken and digested in the same way as soil samples (section 2.2.2. iii.).

Total nitrogen was determined using the Kjeldahl method. A 5 ml aliquot of the digest was taken and mixed with 10 ml of 40 % NaOH (40 g/100 ml distilled water) and steam distilled. The distillate was collected in 50 ml of 2 % boric acid (2 g/100ml distilled water) with four drops of an indicator. The indicator solution was prepared by mixing in a 100 ml volumetric flask, 0.2 g methyl red and 0.13 g bromocresol green and making to the mark with alcohol. The distillate was titrated with 0.096M hydrochloric acid using a micro-burette until the indicator changed from green through grey to a definite pink end point.

Total P was determined colorimetrically, in the same way as soil samples, after colour development with an ammonium molybdate/ammonium metavanadate mixed colour reagent (Okalebo *et al.*, 1993). Absorbances were measured at 450 nm wavelength using a UV/Visible spectrophotometer.

Total bases calcium and magnesium, were determined using an atomic absorption spectrophotometer and potassium and sodium using a flame photometer.

ii) Total organic C

Organic matter content of oven dry (60 °C) foliar and litter samples was determined by slowly igniting about 10 g sample in a muffle furnace to a temperature of 550 °C (Okalebo *et al*, 1993). The loss in weight represents the organic matter content of the sample. The residue represents the ash. Organic carbon in the samples was determined from the following relationship:

$$\%\ Organic\ C\ = \frac{\%\ Organic\ Matter}{1.72}$$

iii) Lignin (ADL), cellulose, hemicellulose and polyphenol

Lignin, cellulose and hemicellulose contents of litter were determined by the acid detergent fibre (ADF) method (Goering and Van Soest, 1970) and polyphenol by the Folin-Denis method as outlined by Anderson and Ingram (1993).

About 1 ± 0.001 g (W1) of ground sample was weighed into a reflux flask. The sample was refluxed for 1 hr with 100 ml acid detergent solution (100 g cetyltrimethyl ammonium bromide in 5 L 0.5 M sulphuric acid) and 2 ml decahydronaphalene to prevent frothing. The sample was filtered through a tared crucible, and the residue washed with 3 x 50 ml aliquots of boiling water. The residue (ADF) was finally washed with acetone until no more colour was removed before being oven dried at 105°C for 2 hours. After drying the ADF sample was weighed (W2) and placed in a crucible for the determination of lignin. The crucible was placed in a pan with 1 cm depth of distilled water. 25 ml of permanganate/buffer was added to the ADF sample in the crucible stirring with a glass rod to break up lumps. The solution was allowed to stand for 90 minutes, adding permanganate where necessary to maintain a purple colour. The crucible was removed from the pan, half filled with demineralising solution, filtered under suction and washed with demineralising solution until white. The white residue was washed with boiling distilled water and then acetone and then sucked dry. The

sample was dried in an oven over night, cooled in a desiccator and weighed (W3). The loss in weight from ADF, that is, W2-W3, is the lignin content.

The sample contents in the crucible were ashed at 550 °C for 1 hour, cooled in a desiccator and weighed (W4).

Calculations:

$$\text{Lignin (\%)} = \left(\frac{W2 - W3}{W1}\right) x100$$

$$\text{Cellulose (\%)} = \left(\frac{W3 - W4}{W1}\right) x100$$

Neutral detergent fibre (NDF) was determined in a similar way as ADF but a neutral detergent solution was used instead of an acid detergent solution. The residue obtained was finally washed with acetone until no more colour was removed before being oven dried at 105°C for 2 hours. After drying the NDF sample was weighed (W5). The difference between NDF and ADF gives the hemi-cellulose content.

$$\text{Hemi-cellulose (\%)} = \left(\frac{W5 - W2}{W1}\right) x100$$

Polyphenols were determined using the Folin-Denis method. About 0.75 ± 0.001 g (W6) of ground sample was weighed into a beaker and 20 ml 50 % methanol was added. The sample was covered with a parafilm and placed in a water bath for 1 hour at 77-80 °C. The extract was quantitatively filtered (Whatman No. 1) into a 50 ml volumetric flask using 50 % methanol to rinse and made to the mark with water. After mixing well a 1 ml aliquot was pipetted out into a 50 ml volumetric flask. 20 ml of water, 2.5 ml Folin-Denis reagent and 10 ml of sodium 17 % carbonate were added and the solution made to the mark with water, mixed well and made to stand for 20 minutes

before reading absorbance at 760 nm. Standards were prepared in the same way as the 1 ml aliquot and the absorbance was also read at 760 nm. A standard curve of absorbance against concentration was used to find the concentration of polyphenols. Polyphenols were expressed as a percentage of the weight of the plant material sample used.

2.2.4 Analyses of water samples

Water samples collected from rain gauges and pan lysimeters were analysed for NH_4^+-N, NO_3^--N, pH, Ca, Mg, K and Na.

Mineral N, that is, ammonium-N and nitrate-N, was determined using the method described by Okalebo *et al* (1993). The ammonium and nitrate nitrogen were determined using the Kjeldahl method (Okalebo *et al*, 1993).

A 10 ml aliquot of the water sample was distilled after adding approximately 0.2 g MgO. The MgO was first ignited in a muffle furnace for 2 hours at 600-700 ^{o}C, cooled and stored in a tightly stoppered bottle. The distillate was collected in a conical flask with 5 ml boric acid with indicator solution. The amount of ammonium-N was determined by titrating with 0.001 N H_2SO_4 in a microburette to a permanent faint pink colour.

Nitrate nitrogen was determined in the same sample used to determine ammonium nitrate, by adding approximately 0.2 g Devarda's alloy to the sample to reduce nitrate-N to ammonium-N. The sample was distilled again into fresh boric acid in another receiving flask. The amount of nitrate-N was determined by titrating as before with 0.001 N H_2SO_4 in a microburette to a permanent faint pink colour.

The cations, calcium and magnesium were determined using the Atomic Absorption Spectrophotometer. Potassium and sodium were determined using the Flame Photometer.

3. VEGETATION STRUCTURE AND CHARACTERISTICS OF THE STUDY SITES

3.1. INTRODUCTION

Vegetation structure and characteristics of a forest or woodland are very important because they determine nutrient dynamics. The vegetation in an area determines the chemistry of throughfall and stem flow by altering concentrations of elemental composition of incident precipitation (Parker, 1983). Vegetation is an important soil forming factor contributing to soil organic matter which in turn influences the chemistry of the soil (Buol *et al.*, 1989; Brady and Weil, 2002). The amount of nutrients taken up by vegetation and cycled through litter fall depends on the vegetation in an area. The intensity of fires that may occur depends on the time of the burn and the fuel load in the area. The fuel load is a function of the vegetation especially the herbaceous layer. Understanding vegetation characteristics of a woodland or forest ecosystem is therefore a prerequisite for understanding nutrient dynamics.

This chapter describes the herbaceous and woody vegetation found in the experimental areas at the two study sites, Mukuvisi Woodlands and Henderson Research Station. Information on vegetation will provide a foundation for understanding nutrient dynamics in the miombo woodlands.

3.2 SAVANNA VEGETATION

3.2.1. Introduction

Savannas are characterized by a continuous grass layer and a variable layer of woody plants determined by the variation in environmental factors (Frost, 1996). The proportion of the herbaceous layer and the woody plants is determined mainly by water and soil nutrients with fire, herbivory and past clearance playing a modifying role (Huntley and Walker, 1982, Stott, 1991). In some savanna areas elephants (Guy, 1989) and stochastic events such as, frost, insect invasions, drought and flooding (Walker,

1981), also modify vegetation by destroying some trees. Savannas are therefore dynamic systems varying markedly from place to place according to reasonably well known variables. The study sites cover a representative savanna pattern found in the central Zimbabwean highveld region.

3.2.2. Classification of savannas

Researchers have classified savannas using different criteria. Such classification facilitates comparison of different savanna vegetation formations (Walker, 1981; Johnson and Tothill, 1985; Stott, 1991) and they also reflect our knowledge and understanding of these ecosystems. Walker (1981) grouped savannas on the basis of soil texture and rainfall. Johnson and Tothill (1985) grouped the world's savannas into 3 broad, major savanna types on the basis of rainfall and nature of the grass layer. In their classification, the first group is dominated by Panicoid and Andropogonoid grasses and it occurs in areas where rainfall is above 1500 mm per annum. The second group has an annual rainfall range of 750-1500 mm and is dominated by Andropogonoid grasses. The majority of savanna lands of the world fall into this group. Aristoid and Eragrostoid grasses dominate the third and drier savanna type. In this group, rainfall average is less than 750 mm per annum.

The floristic variation in these 3 groups is determined by annual rainfall and soil textural characteristics, both factors affect soil moisture, soil texture through water holding capacity. The African savannas, which are of interest in this research project fall into the second group. They occupy 15 million km^2 (Menaut *et al.*, 1985). The general distribution of the grass genera in these vegetation types is summarised in Table 1.

Savanna vegetation formations have also been classified on the basis of the prime factors, plant available moisture (PAM) and plant available nutrients (PAN (Stott, 1991). This classification places savanna formations on a plane with PAM and PAN as axes. Stott (1991) defines PAM as the length of time during which water is available in the soil or the length of time during which rainfall exceeds evapotranspiration and PAN

as the sum of exchangeable bases, K^+, Ca^{2+}, Mg^{2+} and Na^+ in the soil. Figure 3.1 shows that miombo woodlands have low PAN and high PAM, implying that they are nutrient limited.

Table 3.1. Distribution of grass genera within African savanna systems (Source: Johnson and Tothill, 1985).

	SOIL-WATER RELATIONS DRY ◄——► WET		
HUMID SAVANNA (1000-1800mm)	***Arundinelleae*** *(Loudetia, Tristachya)* ***Andropogoneae*** *(Hyparrhenia, Trachypogon)*	***Andropogoneae*** *(Hyparrhenia, Andropogon)*	***Paniceae*** *(Echinochloa, Panicum, Paspalum)* ***Oryzeae*** *(Oryza, Leersia)* ***Arundineae*** *(Phragmites)*
SUBHUMID SAVANNA (750-1000mm)	***Arundinelleae*** *(Loudetia)* ***Andropogoneae*** *(Andropogon, Hyparrhenia)*	***Andropogoneae*** *(Hyparrhenia, Andropogon)*	***Andropogoneae*** *(Hyparrhenia, Andropogon)*
SEMI-ARID SAVANNA < 750mm	Aristideae *(Aristida)*	***Paniceae*** *(Cenchrus)* ***Erasgrostideae*** *(Eragrotis, Trichoneura)* ***Chlorideae*** *(Chloris, Ctenium)* ***Aristideae*** *(Aristida)* ***Andropogoneae*** *(Hyparrhenia, Andropogon, Dichanthium, Bothriochloa)*	***Andropogoneae*** *(Hyparrhenia, Andropogon)*
	SOIL TEXTURE SAND ◄——► CLAY		

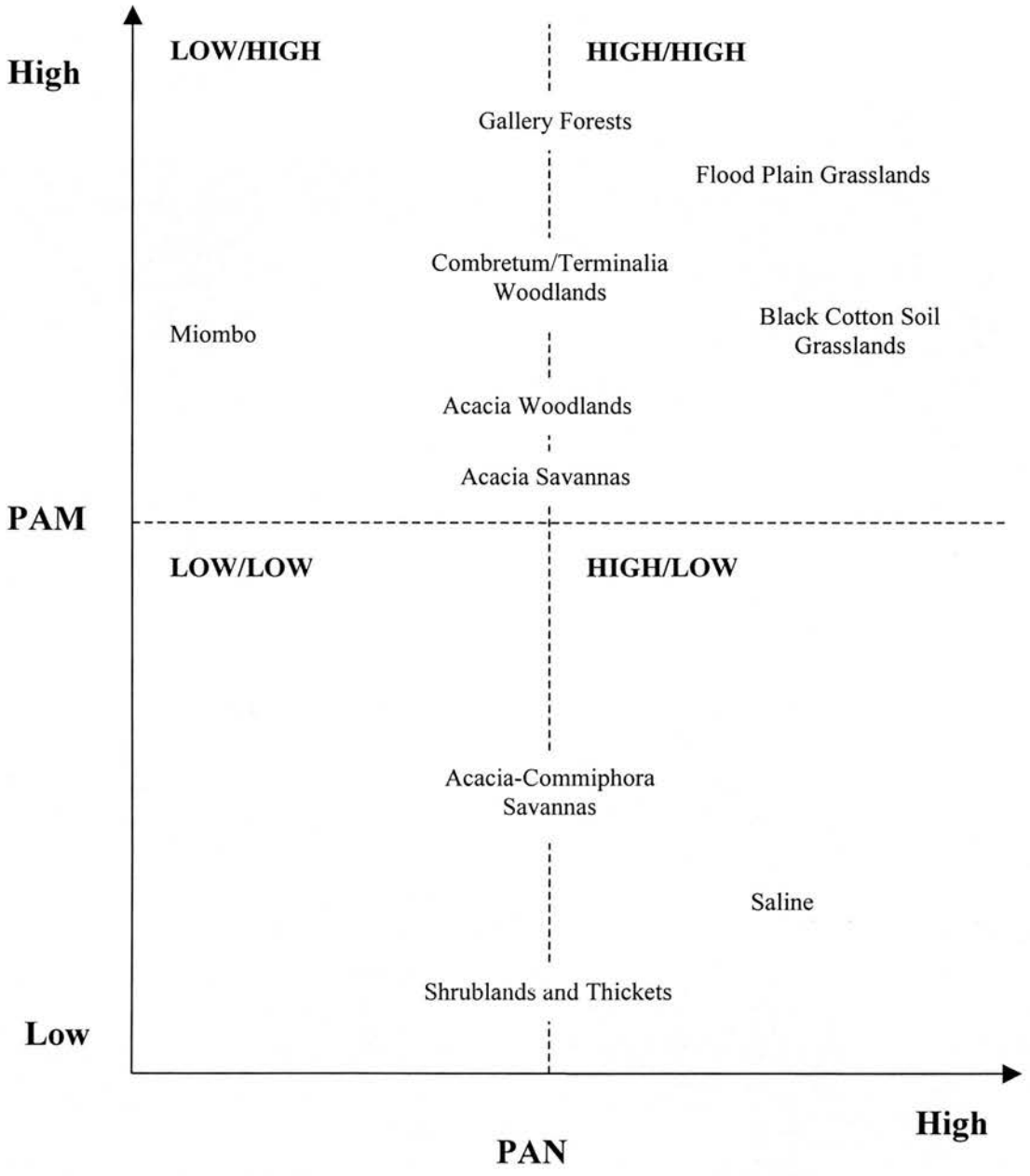


Figure 3.1. A classification model of tropical savannas based on PAM/PAN axes. Miombo are shown as having low plant available nutrients (PAN) and high available moisture (PAM) (Source: Stott, 1991).

Vegetation can also be classified or distinguished on the basis of the dominant genera. African savanna woody plants are, in general dominated by the genera, *Brachystegia, Isoberlinia, Julbernardia* and *Daniella* in the family *Fabaceae* and the first three genera dominate in miombo woodlands. *Terminalia* and *Combretum* in the family *Combretaceae* are next in importance. *Acacia* and *Cochlospermum* (*Cochlospermaceae*) are important in lower rainfall areas and *Borassus* in swamps. In southern Africa, miombo and *Colophospermum mopane* woodlands are all included in the savanna concept (Huntley, 1982). The more arid savannas are represented by the tree genera *Acacia, Commiphora, Colophospermum* and grass genera *Rhigozum, Stipagrotis, Panicum, Enneapogon* and *Aristida* (Huntley, 1982). The relatively moist southern Africa savannas are characterised by the tree genera, *Brachystegia, Julbernardia, Burkea, Ochna* and grass genera *Andropogon, Schizachyrium* and *Loudetia (*Walker, 1982). Frost (1996) however reports that *Hyparrhenia, Andropogon* and *Loudetia* are the dominant grass species in this region. Mixtures of arid and moist savanna genera may occur, especially in intermediate rainfall zones (Huntley, 1982; personal observation).

Most of the savanna research work has grouped and described vegetation patterns on a regional and large-scale community basis (Walker, 1987). The need for small-scale vegetation studies has been realised (Campbell *et al.*, 1995; Walker, 1987) and such studies at greater resolution are needed to understand these ecosystems. Understanding the vegetation pattern is a good starting point in understanding ecosystem function and characteristics such as nutrient dynamics.

3.2.3. Methods of studying vegetation

Smith (1980) outlines some field methods that can be used for sampling plant populations. The main methods used are quadrats, belt transects and plot-less methods such as line intercepts and point-quarters. Quadrats are plots used for studying vegetation and it is the most popular and easy to use method. Depending on the vegetation community, quadrats may vary in size, shape and the number used in an area. The accuracy of quadrat sampling depends on the number and distribution of the

quadrats in an area. A belt transect is a cross section of an area used for recording, mapping or studying vegetation. This method is suitable for estimating abundance, frequency and distribution of vegetation. It is also possible to relate vegetation changes to changes in the environment, such as, slope, soils, and drainage because of the continuity of the transect through the area. The line intercept or line transect involves taking observations on a line or lines laid out randomly or systematically over a study area. The method is rapid, objective and well suited for measuring changes in vegetation in an area but it is however not well adapted for estimating frequency or abundance. The line intercept can, however, be used in conjunction with quadrats, thus overcoming some of its weaknesses. The point-quarter or plot-less method involves measuring and recording trees or plants from random points. Lines are drawn through selected points to form 4 equal quarters and the plant in each quarter nearest to the centre point is recorded. The method is well adapted for sampling vegetation communities in which plants are widely spaced or where the large trees or shrubs are the dominant plants in relatively homogenous tracts of vegetation.

Vegetation patterns in an area can also be determined by remote sensing and/or field surveys of species abundance using methods described above. Biomass determination is often added using regression equations for trees (Abbot *et al.,* 1997; Guy, 1981; Grundy, 1995; Eshete and Stahl, 1998 and Stromgaard, 1986b) and herbaceous plants by harvesting and weighing plant material from a quadrat of known area (Anderson and Ingram, 1993; Chidumayo, 1997). Rutherford (1982) defines biomass as the amount of living or supportive material (phytomass) in a plant community and is expressed as dry mass excluding attached dead material (necromass). There is generally a positive correlation between plant biomass and rainfall (Bell, 1982), though a few exceptions do occur as in *dambos/vleis* and floodplains occurring at lower elevations near base level in the midst of woodlands/forests.

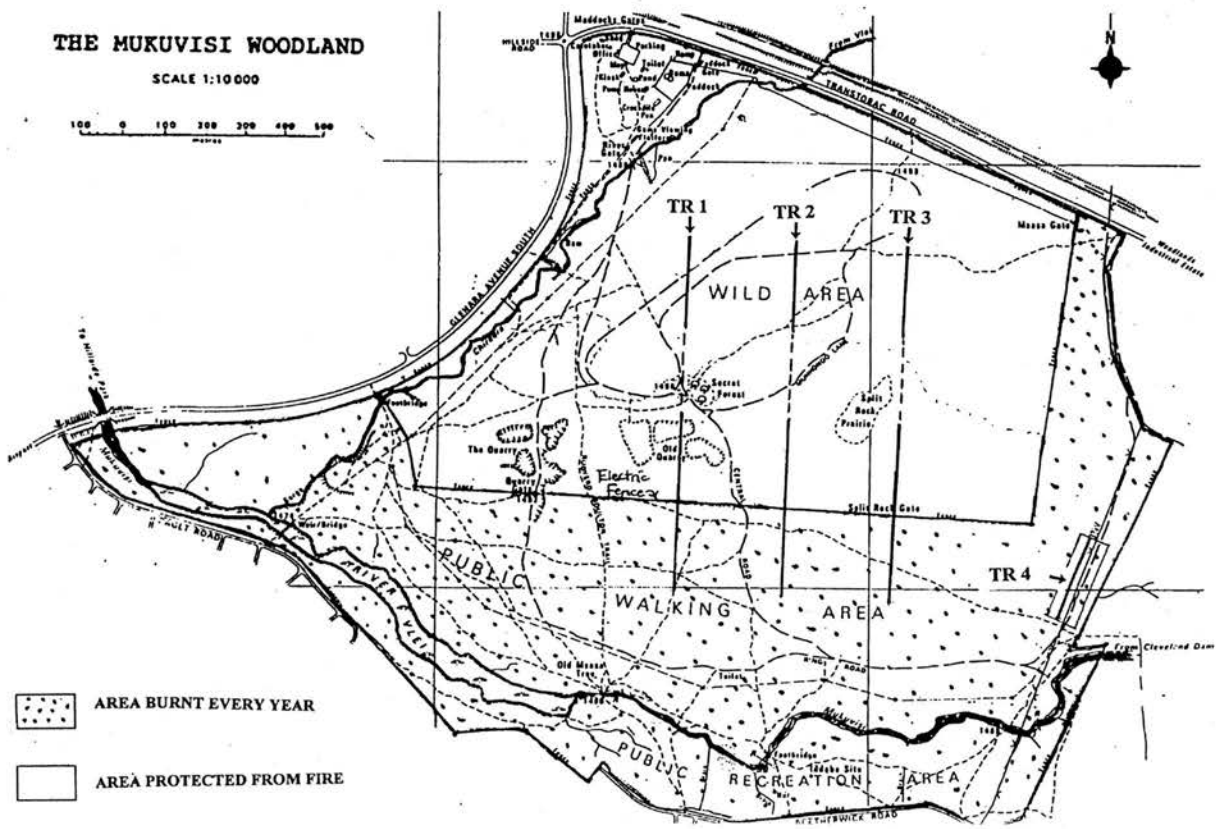
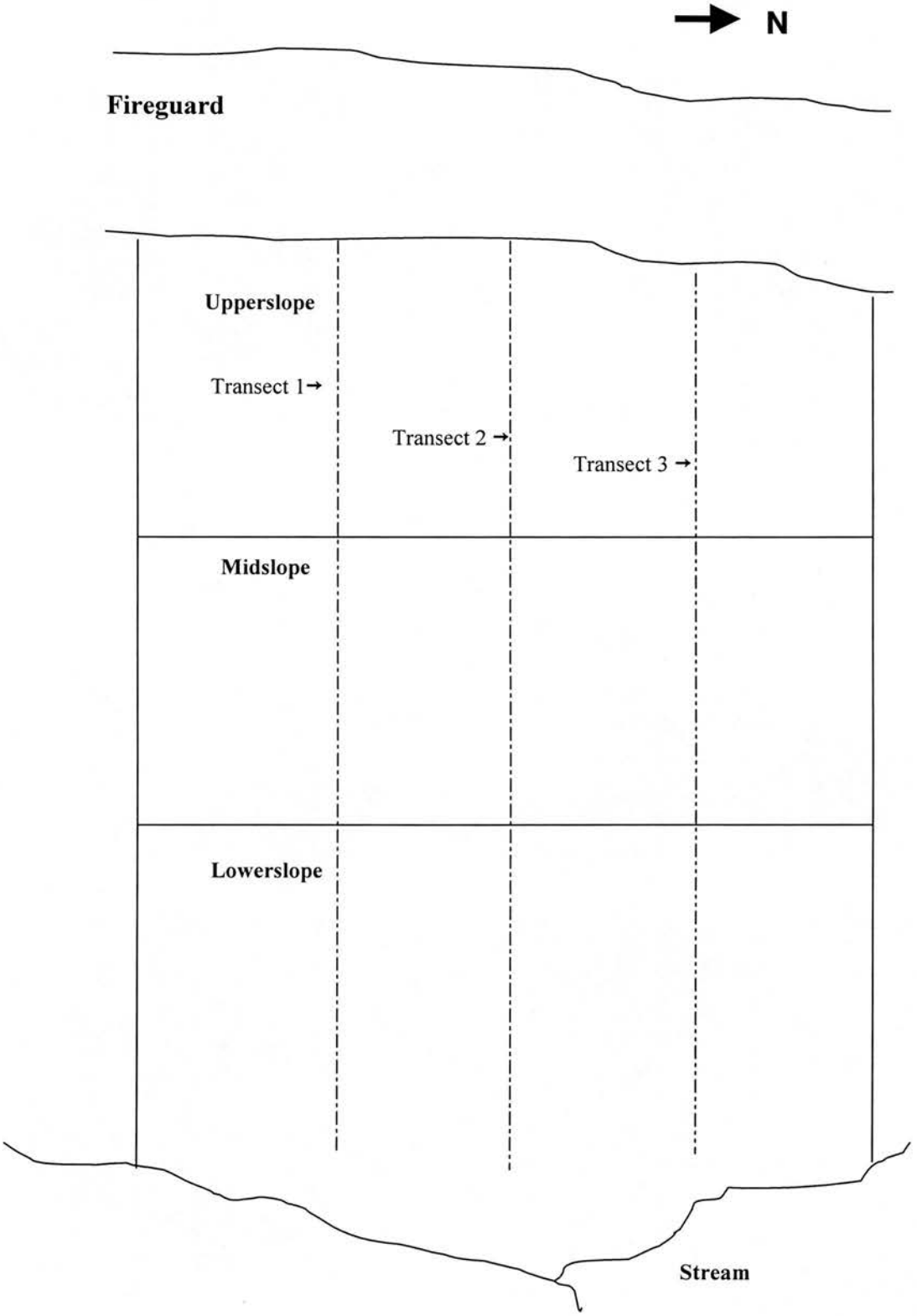


Figure 3.2. Map at an approximate scale of 1 : 10000 showing the transects along which measurements were taken at Mukuvisi Woodlands experiment sites. Transects 1 to 3 passes through the Wild Area and the Public Walking Area. The Wild Area inside the fence comprises the miombo woodland (Muk-Prot) and grassland areas (Muk-Grass) protected from fire. The grassland area sampled in this study, that is the northern end of the transects, is up to the dotted section of the transects on the map, where Muk-Prot starts. Most of the measurements in Muk-Prot were carried out along the bold section of the transect close to the fence. The Public Walking Area is burnt annually and transects 1 to 3 go through the burnt miombo woodland area (Muk-Prot). Transect 4 is in the deforested burnt area (Muk-Def).

Figure 3.3. Map at an approximate scale of 1cm : 40m showing the transects along which measurements were taken at Henderson Research Station experiment sites.



Assessment of species and biomass of grass species is commonly achieved using 1 x 1 m quadrats (Anderson and Ingram, 1993; Chidumayo, 1997) from which the herbaceous material is identified and harvested. There are, however, variations in the number of quadrats sampled per unit area, with the intensity or scale of the study and/or logistics being the major factors. The methods used for woody plants are varied especially the sample areas used. The variability is mainly on the area used for making tree measurements. Guy (1981) used transects 50 x 100 m running across a study area, Grundy *et al.* (1993) used plots ranging from 20 x 20 m to 100 x 100 m, Grundy (1995) used 0.5 ha plots and Campbell *et al.* (1995) used 10 x 10 m plots. In some cases single trees are randomly selected rather than all trees in an area for biomass measurement (Abbot *et al.*, 1997; Eshete and Stahl, 1998). The size of the study area and the complexity of the vegetation pattern generally determine the sample area size. Smith (1980) however, recommends the use of nested quadrats to determine the minimum size of area to adequately describe vegetation in an area.

Where minimum diameter of stems sampled and height above ground are standardized, the basal stem area can be used to provide a measure of tree biomass (Rutherford, 1982). Stem basal area can be calculated using either stem diameter or circumference (Anderson and Ingram, 1993). The basal area of a woodland of *Brachystegia spiciformis, Julbernardia globiflora* and *Burkea africana* in Masvingo, Zimbabwe for trees with stems with diameter greater than 2.5 cm was found to be 8.3 m^2/ha (Ward and Cleghorn, 1964). In the Zimbabwe highveld, the basal area of a *B. spiciformis, J. globiflora* and *B. africana* woodland was 10.8 m^2/ha (Strang, 1974). Campbell *et al.* (1995) found the combined basal area of *B. spiciformis* and *J. globiflora* to be 8.6 m^2/ha. Basal area measurements can be determined on a dominant species basis or on sum total basis (Rutherford, 1982).

In view of the above discussion a combination of quadrats and transects were selected as the appropriate method for this study and the methods are outlined in detail in section 3.3. below.

3.2.4. Objectives

The objective of this study was to measure and compare herbaceous biomass and woody tree basal area in the experiment areas at Henderson Research Station and Mukuvisi Woodlands.

It was hypothesized that Muk-Burn has higher herbaceous biomass and lower woody plant biomass compared to Muk-Prot because of burning. It is also hypothesized that Henderson study areas, Hen-Up, Hen-Mid and Hen-Low have higher woody and grass biomass compared to Mukuvisi Woodland sites because they have heavier and relatively more fertile soils.

3.3 MATERIALS AND METHODS

3.3.1. Study Sites

Four experiment areas were identified and used in this study at Mukuvisi Woodlands (Fig.3.2). The experiment areas were the protected miombo woodland (Muk-Prot), the protected grassland (Muk-Grass), the burnt miombo woodland (Muk-Burn) and the cleared or deforested area (Muk-Def). The areas Muk-Prot, Muk-Burn and Muk-Def are on a well-drained, upper slope position. The land gently slopes ($\leq$ 1 % slope) to the grassland area on the middle slope topographic position. This area occasionally experiences a high fluctuating water table during the rain season and is characterised by a few scattered *Parinari curatellifolia* trees. The grassland area stretches to the lower slope where it is progressively wetter. The extremely wet area stretches to a stream. The grassland area used in this study is in the middle slope area.

At Henderson Research Station, three experimental areas occupying different catenal positions were identified (Fig. 3.3). They were the area on the upper slope (Hen-Up) with gravelly and stony, well drained soils, the middle slope area (Hen-Mid), with moderately deep ($\approx$100 cm), well-drained soils and the lower slope area (Hen-Low), with deep (120 cm+), moderately well drained soils. The upper slope catenal position

and has a slope range of about 5 to 8 % compared to 2 to 3 % and 1 to 2 % at Hen-Mid and Hen-Low experiment areas respectively.

3.3.2. Methods for sampling and studying vegetation

In this study a combination of line transects running along the slope and quadrats located at regular distance on transects were used (Stromgaard, 1986a). This method was preferred because representative samples along the whole length of the experiment areas could be collected. It was hoped that variations due to slope, any within experiment area drainage effects and uneven burning (in Muk-Burn) would be accounted for. Line transects were located at both study areas using a compass, a 100 m tape measure and 1.2 m wooden pegs which were located every 20 m along the transects. At Mukuvisi Woodlands, three parallel transects, approximately 200 m apart, ran through Muk-Burn, Muk-Prot and Muk-Grass (Fig. 3.2). The second (middle) line transect ran approximately through the middle of the experimental areas. A fourth, short transect was located in the deforested area (Muk-Def). Only one transect was used in Muk-Def because the deforested area is only about 50 m wide. At Muk-Prot and Muk-Burn measurements were taken only using 200 m length along the line transect from the boundary fence between the two experimental areas (Figure 3.2.). At Muk-Def, similarly 200 m of the transect was used. At Muk-Grass the 200 m was measured from the edge of the woodland (Figure 3.2.).

At Henderson Research Station, 3 parallel transects were also located but these were 50 m apart because the study sites were smaller. The middle transect was also located such that it ran along the slope, approximately through the middle of the experimental areas, upper slope (Hen-Up), middle slope (Hen-Mid) and lower slope (Hen-Low). The experimental areas at Henderson were identified and separated on the basis of catenary position occupied.

3.3.3. Measurement of grass species occurrence and abundance

Grass species composition was determined in March/April 2000 using 1 m^2 quadrats. For the Mukuvisi Woodland site, quadrats were located 40 m apart along each transect.

This resulted in 5 quadrats per transect per experiment area. Thus Muk-Burn, Muk-Prot and Muk-Grass had each a total of 15 quadrats. The deforested area, Muk-Def, which had only one transect running through, had a total of 5 quadrats.

At Henderson Research Station, quadrats were also located along three transects. A total of 6 quadrats were located along each transect, with each two quadrats falling into the experiment areas, comprising Hen-Up, Hen-Mid and Hen-Low at different topographic positions. Each experiment area therefore had a total of 6 quadrats.

Grass species were harvested from each quadrat using a sickle. It was not possible to cut the grass at ground level. The grass species were therefore cut at 2.5 cm from above the ground (Chidumayo, 1997) and each species was put into a separate labeled khaki paper bag. Species samples collected from the quadrats were oven-dried at 60 ^{o}C and weighed to find the dry matter biomass. Samples for identifying the species found in each quadrat were taken during the same time outside the quadrats and careful placed between newspaper pages and pressed for a few days. After air-drying these samples were taken for species identification at the Botanic Gardens Herbarium, a unit of the Department of Research and Specialist Services in the Zimbabwe Ministry of Lands and Agriculture.

3.3.4. Measurement of woody species occurrence and abundance

Woody tree species at the study sites were identified in plots along the line transects. The woody plant species of height $\geq$ 0.5 m in the plots were measured using aluminium height-rods. Diameter was measured at 1.2 m from the ground, that is, at diameter at breast height (*dbh*), for all woody plants with a height greater than 1.2 m using a diameter tape measure. Stem basal area was calculated using *dbh* for all trees and woody plants measured.

The minimum size of plot used at the different study sites was determined by initially making a quick species count using a geometric system of nested plots. At Mukuvisi Woodlands, tree species identification and measurement was done in the woodland

areas Muk-Prot and Muk-Burn. In Muk-Prot, one, 10 m x 20 m plot was located on each line transect making a total of 3 plots in the experiment area. Two plots of 10 m x 20 m were located on each transect in Muk-Burn, making a total of 6 plots in this experiment area. The plots in Muk-Prot and Muk-Burn were randomly allocated to any 3 points on the 200 m transect in each experiment area. Two of the points were 40 m from either end of the transect and the third point was located in the middle, between the other 2 points. More plots were located in the burnt area because vegetation distribution was less uniform compared to the protected woodland.

At the Henderson site, 5 m x 14 m plots were located in all the 3 experiment areas on each transect. One plot was located on each transect in each experiment area (topographic position), making a total of 3 plots in each experiment area. The plots were likewise randomly allocated to any 3 points on each transect, in each experiment area. Two of the points were 20 m from either end of the transect within each experiment area and the third point was located in the middle of the transect between the two points.

3.3.5. Data analysis

Data was prepared and tabulated in Excel and means, standard deviations and standard errors calculated. A one-way analysis of variance was used to analyse herbaceous biomass and basal area data. Where the analysis of variance resulted in a significant F-test, multiple pair-wise comparison of means was carried out using Fisher's Least Significance Difference method to identify pairs of means that are significantly different.

3.4 RESULTS

3.4.1. Herbaceous biomass and species composition

The mean total herbaceous biomass was highest at Muk-Grass (193.6 ± 23.27 g/m^2) followed by Hen-Low (167.9 ± 30.60 g/m^2), Muk-Prot (164.7 ± 21.17 g/m^2), Muk-Burn

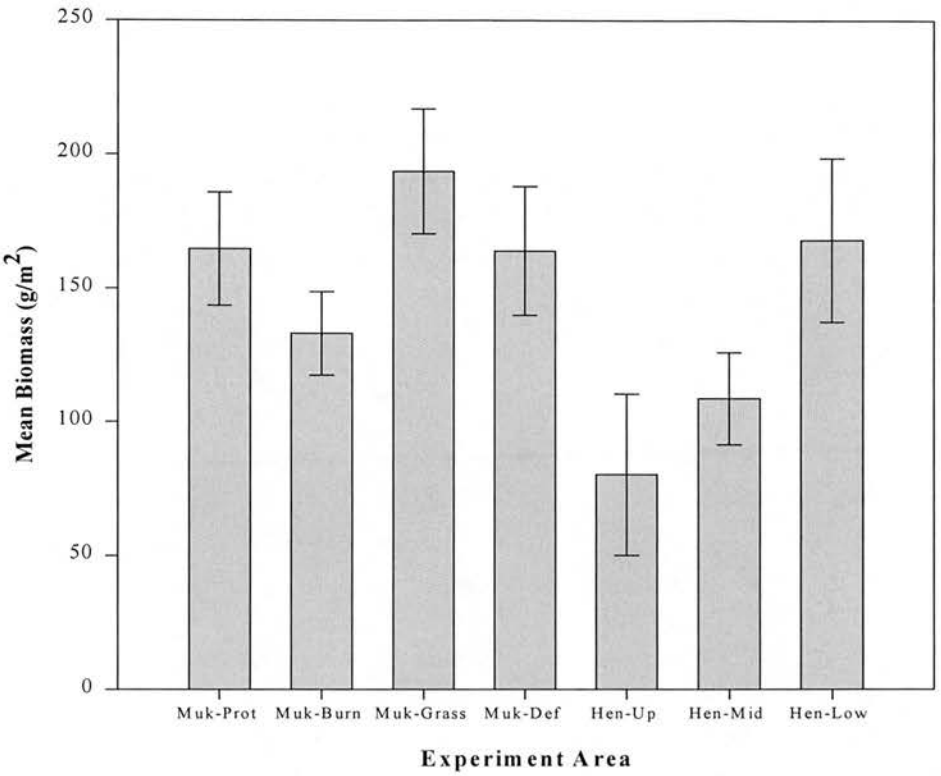


Figure 3.4. Herbaceous biomass (g/m^2) in experimental areas Muk-Prot^{ab} (n=15), Muk-Burn^{ac} (n=15), Muk-Grass^{b} (n=15), Muk-Def^{ab} (n=5), Hen-Up^{d} (n=6), Hen-Mid^{cd} (n=6) and Hen-Low^{ab} (n=6) at Henderson Research Station and Mukuvisi Woodlands. Bars represent standard errors of means. Experimental areas with the same letter are not significantly different ($p<0.05$; Fischer LSD Test).

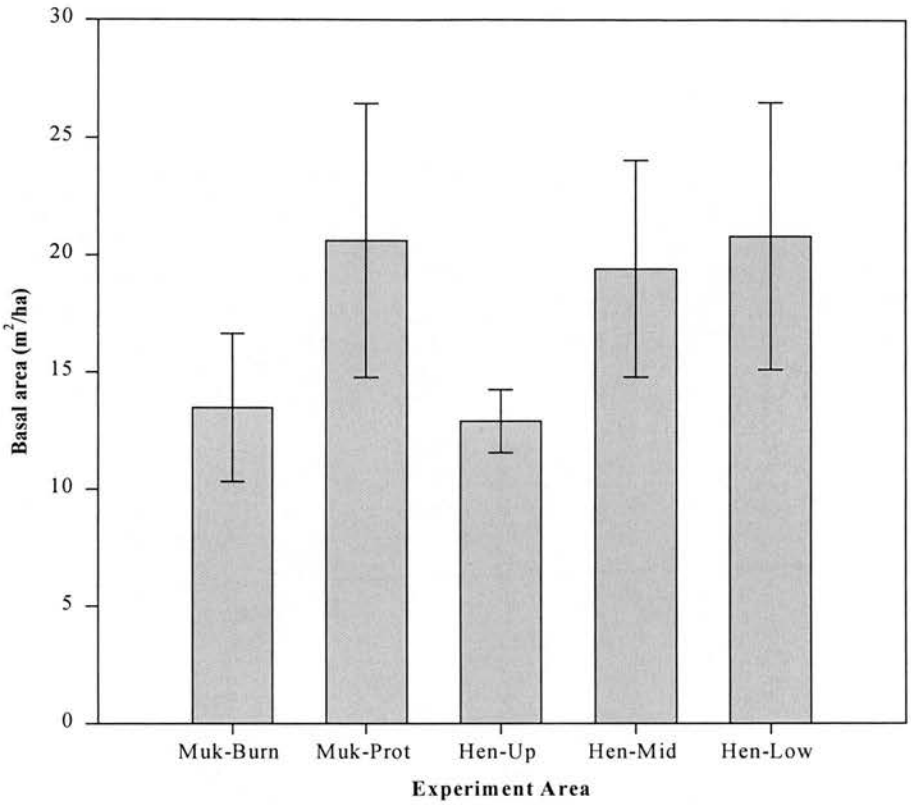


Figure 3.5. Basal area (m^2/ha) of trees at experimental areas Muk-Burn (n=6), Muk-Prot (n=3), Hen-Up (n=3), Hen-Mid (n=3) and Hen-Low (n=3) at Henderson Research Station and Mukuvisi Woodlands experimental areas. The mean basal areas showed no significant difference at $p<0.05$.

Table 3.2. Total number of herbaceous species and mean total biomass (g/m^2) of the dominant herbaceous species at Mukuvisi Woodlands and Henderson Research Station experiment areas

Experiment area	No. of plots	No. of species identified	Dominant species	Mean total biomass (g/m^2)	Standard Deviation
Muk-Prot	15	43	*Hyparrhenia filipendula*	54.92	22.13
			Chloridion cameronii	25.05	7.20
			Sporobolus pyramidalis	17.56	6.24
			Schizachyrium jeffreysii	9.97	4.33
Muk-Grass	15	17	*Sporobolus pyramidalis*	95.30	13.25
			Hyparrhenia filipendula	48.33	12.39
			Asparagus africanus	8.49	8.49
			Schizachyrium jeffreysii	8.41	4.00
Muk-Burn	15	14	*Hyparrhenia filipendula*	28.62	13.35
			Schizachyrium jeffreysii	16.36	10.10
			Chloridion cameronii	12.39	2.84
			Rynchelytrum nyassanum	11.65	5.86
Muk-Def	5	13	*Hyparrhenia filipendula*	69.32	36.65
			Hyparrhenia rufa	29.35	18.63
			Chloridion cameronii	14.56	6.69
			Melinis repens	13.62	13.62
Hen-Up	6	21	*Hyparrhenia newtonii*	23.73	16.29
			Eragrotis sclerantha	13.79	7.67
			Themeda triandra	10.35	10.35
			Desmodium uncinatum	6.95	6.84
Hen-Mid	6	13	*Sporobolus pyramidalis*	25.82	6.14
			Schizachyrium jeffreysii	20.85	9.94
			Eragrotis sclerantha	19.86	9.75
			Fimbristylis hispidula	13.52	7.07
Hen-Low	6	12	*Sporobolus pyramidalis*	88.46	28.50
			Hyparrhenia filipendula	43.16	27.63
			Heteropogon contortus	21.55	11.08
			Themeda triandra	10.94	6.92

Table 3.3. Total stem density for all species and stem density (>2.5 cm diameter) of dominant tree species at Henderson Research Station and Mukuvisi Woodlands experiment areas

Experiment Area	Dominant Tree Species	Total Stem Density (stems/ha) (for dominant species)		Total Stem Density (stems/ha) (for all tree species)	
		0.5 - 3 m	3 - 15 m	0.5 - 3 m	3 - 15 m
Muk-Burn	*J. globiflora,*	1427	129	2359	496
	B. spiciformis	324	118		
Muk-Prot	*J. globiflora,*	1133	1300	1976	1867
	B. spiciformis	510	243		
Hen-Up	*J. globiflora,*	196	498	592	1198
	B. spiciformis,	149	350		
	B. boehmii	196	251		
Hen-Mid	*J. globiflora,*	115	805	564	1941
	B. spiciformis,	170	617		
	B. boehmii	165	456		
Hen-Low	*B. boehmii*	341	854	506	1533
	B. spiciformis	110	624		

Table 3.4 Total number of woody species, dominant tree species, total basal area (for all tree species) (m^2/ha) and height of the tallest trees at Henderson Research Station and Mukuvisi Woodlands experiment areas (sd. – standard deviation).

Experiment Site	No. of woody species	Dominant species	Total basal area (m^2/ha) (sd.)	Height of tallest tree (m)
Muk-Burn (n=6)	**20**	*J. globiflora*, *B. spiciformis*	**13.5** (7.7)	**12**
Muk-Prot (n=3)	**9**	*J. globiflora*, *B. spiciformis*	**20.6** (10.1)	**8.5**
Hen-Up (n=3)	**6**	*J. globiflora*, *B. spiciformis*, *B. boehmii*	**12.9** (2.3)	**10.0**
Hen-Mid (n=3)	**10**	*J. globiflora*, *B. spiciformis*, *B. boehmii*	**19.4** (8.0)	**11.8**
Hen-Low (n=3)	**3**	*B. boehmii* *B. spiciformis*	**20.8** (9.9)	**12.3**

and Muk-Def (163.9 ± 24.07 g/m^2), Muk-Burn (133.0 ± 15.66 g/m^2), Hen-Mid (108.7 ± 17.29 g/m^2) and Hen-Up (80.2 ± 30.18 g/m^2) with the lowest (Figure 3.4).

The dominant grass species at the Mukuvisi experimental sites *are Hyparrhenia filipendula, Chloridion cameronii, Sporobolus pyramidalis, Schizachyrium jeffreysii, Asparagus africanus, Rynchelytrum nyassanum, Hyparrhenia rufa* and *Melinis repens* (Table 3.2). At Henderson Research Station experimental sites, *Hyparrhenia newtonii, Eragrotis sclerantha, Themeda triandra, Desmodium uncinatum, Sporobolus pyramidalis, Schizachyrium jeffreysii, Fimbristylis hispidula, Hyparrhenia filipendula* and *Heteropogon contortus* (Table 3.2) are the dominant species. Appendix 1. shows the biomass of all species found in the quadrats sampled.

3.4.2 Woody vegetation structure and species composition

At Muk-Burn site, *J. globiflora* is the dominant woody tree species on the basis of total stem count (>0.5 m) (Table 3.3). Considering trees > 3 m in height, both *J. globiflora* (129 stems) and *B. spiciformis* (118 stems) are the dominant species. The burnt woodland site is dominated by an under-storey (woody species < 3 m height) which constitutes about 82 % of the total number of stems. Burning resulted in more small trees. In the protected woodland, Muk-Prot, the same pattern is evident with *J. globiflora* being the dominant species. However, the number of *J. globiflora* (> 3 m) stems (1300) is much higher than the number of *B. spiciformis* stems (243). Protection from fire enable small trees to develop into bigger trees. Fire prevents this by destroying new growth and in some cases the whole shoot. The under-storey in the protected woodland has a marginally higher number of stems (51.4 %) compared to tree stems (48.6 %). Tree stems > 3 m are more than three times greater in the protected woodland compared to the burnt woodland.

At Hen-Up and Hen-Mid sites *J. globiflora*, *B. spiciformis* and *B. bohemii* are the dominant species (Table 3.4). *J. globiflora* has the highest number of stems followed by *B. spiciformis,* with *B. bohemii* being the third highest. At Hen-Low site the situation is reversed with *B. bohemii* having the highest number of stems followed by *B.*

spiciformis. *J. globiflora* is absent at this site. At Henderson sites, the trees dominate with under-storey stems (<3 m) making up less than 34 % of the total number of stems.

Muk-Burn had the highest number of woody plant species with Hen-Low having the lowest (Table 3.4). Trees in all the sites were below 13 m in height. The stem basal area of woody plants at the study sites ranged from 13.49 m^2/ha at Muk-Burn to 20.81 m^2/ha at Hen-Low (Table 3.4 and Figure 3.2). Though Hen-Mid had a higher stem count compared to Hen-Low, the basal area was higher at Hen-Low. This can be explained by the presence of a large proportion of *B. boehmii*, *B. spiciformis*, and *Acacia* species trees that had relatively large diameters. Mean basal areas for all experiment areas at Henderson and Mukuvisi showed no significant difference ($p<0.05$).

3.5 DISCUSSION

Hen-Up, which has very shallow and gravelly soils and less soil moisture because it is on the upper slope topographic position, possessed the lowest herbaceous biomass compared to all the experiment areas at Henderson and at Mukuvisi. It was significantly lower than Muk-Prot and Hen-Low ($F_{6,61}=2.37$, $p<0.05$) and highly significantly lower than Muk-Grass ($F_{6,61}=2.37$, $p<0.01$). Hen-Mid contained a similar amount of herbaceous biomass to that at Muk-Burn. Hen-Low had significantly higher herbaceous biomass ($p<0.05$) than Hen-Up. It was however not significantly different from Hen-Mid. The herbaceous biomass at this site was not significantly different from Muk-Grass, MukProt and Muk-Def.

None of the experimental areas at Mukuvisi Woodlands, except Muk-Burn showed significant differences in herbaceous biomass. The biomass at Muk-Burn site was not significantly different from Muk-Prot and Muk-Def sites but was significantly different ($F_{6,61} = 2.37$, $p<0.05$) from Muk-Grass. The biomass in the protected woodland and grassland sites could be low because of herbivory by the animals enclosed in these areas. Burning seems to have marginally affected the herbaceous biomass in the burnt woodland area. Fire can sometimes result in increased productivity because of increased

nutrient availability, removal of suppressive dead leaves and removal of competition (Whelan, 1995).

The Henderson study sites have soils with higher clay contents and are comparatively more fertile than the sandy soils at Mukuvisi Woodlands sites (Appendix 3). It was therefore expected that Henderson sites would have a higher herbaceous biomass and more woody plants. There was however, no significant difference between Muk-Prot and Muk-Burn and the Henderson experiment areas. This could be explained partly by human influence. Some of the trees could have been removed some years ago to encourage growth of grass for cattle grazing. The grass biomass is not significantly higher most likely because of limited moisture. Henderson receives a slightly lower amount of rainfall and has slightly higher maximum temperatures and there is therefore higher evapo-transpiration at this site resulting in greater water stress limiting herbaceous plant production.

There is a great diversity in the dominant grass species recorded in savanna systems. Huntley (1982) reports that moist savannas have *Andropogon, Schizacharium* and *Loudetia* as dominant genera whilst the arid savannas have grass genera *Rhigozum, Stipagrotis, Panicum, Enneapogon* and *Aristida.* According to Frost (1996) *Hyparrhenia*, *Andropogon* and *Loudetia* are the dominant grass species. The two research sites appear, however, to have mixtures of arid and moist savanna grass genera occurring, which is characteristic of intermediate rainfall zones (Huntley, 1982).

Among the dominant species at the Mukuvisi Woodlands *C. cameronii*, *H. filipendula*, *M. repens* and *S. pyramidalis* were present in all the experiment sites. Dominant species and their abundance in the protected woodland and grassland areas could have been affected by grazing animals. Grazing animals affect species dominance and biomass by selectively feeding on certain grass species. This has the effect of increasing the biomass of the unfavoured grass species (Walker, 1981). It is also likely that fire has affected the species present and their abundance in the burnt experiment areas. Like grazing, fire can also be selective, eliminating fire sensitive species. It is however

difficult to assess from the measurements, the extent of the effect of herbivory and fire on species composition.

The dominant species at Henderson Research Station site, occurring in all the 3 experimental areas, are *F. hispidula*, *H. contortus* and *H. filipendula*. The other dominant species were present in at least two of the experiment areas except *H. newtonii,* which was present in only one experimental area. Unlike the Mukuvisi experiment areas that are subjected to different external disturbances, Henderson sites are subjected to a similar external environment, hence similar grass species. Minor vegetation differences can be explained by differences in soil characteristics associated to catenal position occupied.

Small trees and shrubs dominate in Muk-Burn at Mukuvisi. It is likely that the small trees and shrubs are the plants that have been affected by fire resulting in limited growth. Every year the growing plants are burnt resulting in burning and destruction of new growth or in some cases complete burning of the coppicing shoots. The amount of damage to the plant depends on the intensity of the fire. Fires occurring during the period June to early August tend to be less destructive than fires occurring during the peak of the dry season in September and October before the onset of the rain season.

Stem basal area of woody plants at all the study sites were found to be higher than reported by other workers in Zimbabwe (Ward and Cleghorn, 1964; Strang, 1974; Campbell *et al.*, 1995). These differences arise from the diameter size restrictions of trees measured for determination of basal area. In this study all woody plants for which *dbh* could be measured were included, hence the higher basal area result.

3.6. OVERVIEW

From this chapter, Mukuvisi woodland sites have higher stem counts compared to Henderson sites, that is, a higher tree density. At Muk-Burn it appears that burning resulted in a larger number of smaller less mature trees. At this site few trees develop to

larger trees (3-15 m height) because of burning. At Henderson, differences along slope transects are likely to be due to differences in drainage and moisture availability. Hen-Low, a zone of accumulation has a higher herbaceous biomass because of higher moisture availability. At Mukuvisi differences in moisture between Muk-Prot and Muk-Burn is likely to be small because they occupy similar topographic positions. However, Muk-Grass that is further downslope has higher available moisture and greater herbaceous biomass compared to the other Mukuvisi sites.

The number of trees determines the amount of litter cycled and the extent to which precipitation chemistry will be altered. In the following chapters these aspects of nutrient cycling in miombo woodlands will be covered and differences will be related the vegetation characteristics discussed in this chapter.

4. NUTRIENT ADDITIONS IN INCIDENT PRECIPITATION, THROUGHFALL (CANOPY LEACHING) AND STEMFLOW IN MIOMBO WOODLANDS

4.1. INTRODUCTION

Throughfall or canopy leaching can be defined as that precipitation that passes through the canopy to the ground (Eaton *et al.*, 1973; Parker, 1983). Included in this definition is precipitation that passes through canopy gaps lacking a leaching component. Precipitation falling onto the forest or woodland is incident precipitation. The hydrological classification of incident precipitation after passing through the canopy depends on the last surface encountered (Fig. 4.1) (Proctor, 1987). If the water flows along the tree trunk to the ground it is called stem flow (Eaton *et al.*, 1973; Gersper and Holowaychuk, 1971). The rest, which flows through leaves, twigs and branches, to the ground including crown drip is throughfall (Parker, 1983; Proctor, 1987; Bruijnzeel, 1989). The precipitation that is held by vegetation and evaporates into the atmosphere is interception loss (Parker, 1983, Bruijnzeel, 1989). Precipitation passing through the canopy is altered by the interaction with vegetation. This may result in significant nutrient fluxes. Material picked up from the canopy may be from both within the plant and plant surfaces (Ingham, 1950).

This chapter examines the amount of incident precipitation and throughfall at the two miombo woodland sites, Mukuvisi Woodlands and Henderson Research Station and stemflow at Henderson Research Station. The objective of this study was to measure inputs of selected nutrients N (NH_4^+ and NO_3^-), Ca^{2+}, Mg^{2+}, K^+ and Na^+ to miombo woodlands in rainfall, throughfall and stem flow. It was hypothesized that rainfall, throughfall and stem flow add significant amounts of nutrients to miombo woodland soils.

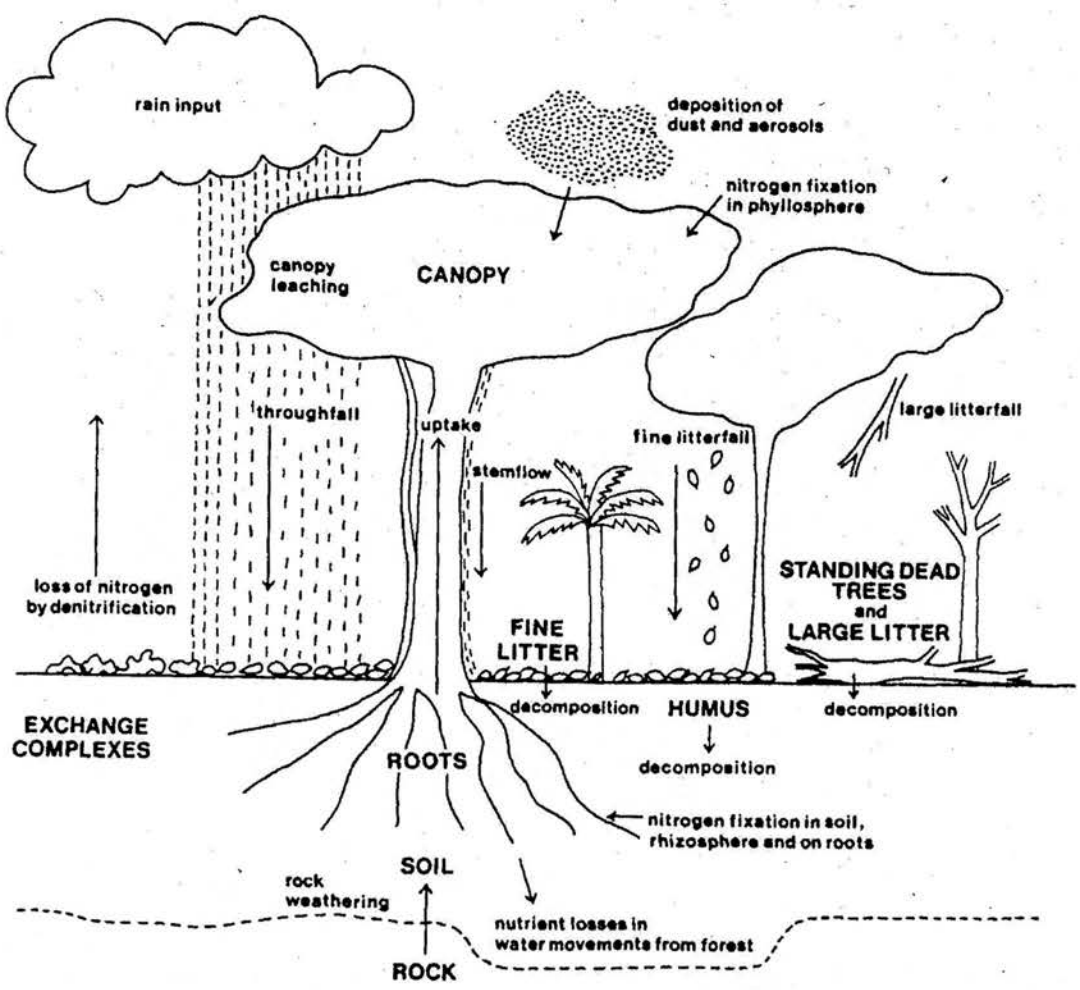


Figure 4.1. A simplified forest nutrient cycle. In the present study nutrients transferred through rainfall, throughfall, stem flow, leaching from soil, fine litter fall and decomposition were measured. (Source: Proctor, 1987).

4.2. ASSESSMENT OF LITERATURE ON THROUGHFALL AND STEM FLOW

4.2.1. Introduction

Rainfall provides one of the largest input of mineral nutrients to many forests (Table 4.1.) and the source of these nutrients, particulate or dissolved, is the atmosphere (Parker, 1983). Not all nutrients in rainfall reach the forest floor. Considering a single rainfall event, some nutrients may be absorbed by foliage or taken up by microflora, some may be deposited on tree surfaces as salts and the rest carried in throughfall and/or stem flow to the soil (Carlisle *et al.*, 1967; Eaton *et al.*, 1973). The movement of water through the canopy depends on the structure and density of the foliage and branches. At the beginning of a rainfall event the canopy is wetted and if the rainfall is heavy the canopy or part of it becomes saturated. After saturation, rainfall then falls to the ground as throughfall or stem flow (Eaton *et al.*, 1973). However, if there are gaps in the canopy, some precipitation will pass through to the ground without being intercepted. Residence time of the water within the canopy will depend on the canopy size, density and morphology, and the amount of precipitation received.

Forest inputs of nutrients in rainfall have been measured in different parts of the world, Amazon rain forest (Jordan, 1982); Malaysian rain forest (Sinun *et al.* 1992); Indonesia forest plantation (Bruijnzeel, 1989); Puerto Rico forest (Jordan *et al.* 1972); New Guinea tropical rain forest (Edwards, 1982), Ivory Coast evergreen forest (Bernhard-Reversat, 1975), U.S.A forests (Gersper and Holowaychuk, 1971; Reiners, 1972; Eaton *et al.*, 1973; Turner and Singer, 1976; Henderson *et al.* 1977; Westman, 1978; Yawney *et al.*, 1978; Brinson *et al.*, 1980), Canadian forests (Kimmins, 1973), U.K. forests (Madgwick and Ovington, 1959, Carlisle *et al.* 1967), Australian eucalyptus forest (Attiwill, 1966) just to mention but a few studies. Studies in Africa are very few especially in southern Africa.

Nutrients added to the forest floor through the canopy as throughfall and stem flow are known to be significant (Parker, 1983) and Table 4.1 shows nutrient inputs in net

Table 4.1. Total annual inputs (kg/ha) of nutrients in net throughfall measured in different parts of the world. (- not measured)

Location, forest type and Author	Rainfall (mm/yr)	Nutrients in net throughfall (kg/ha/year)					
		N	P	K	Ca	Mg	Na
Ghana, Moist semi deciduous forest (Nye, 1961)	1562	12.3	3.7	219.9	29.2	17.9	-
New Hampshire, Northern hardwoods (Eaton *et al.*, 1973)	556	11.71	0.73	30.5	7.6	2.2	0.66
Ivory Coast, Plateau forest (Bernhard-Reversat, 1975)	1800	79.5	2.2	65	39.5	41	-
Scotland, Corsican pine (Miller *et al.*, 1976)	616	0.13	22.0	18.0	17.0	131.0	-
Coastal California, *Eucalyptus globus* (McColl and Bush, 1978)	518	2.3	0.27	11.4	8.5	4.2	16.3
North Carolina, Swamp forest (Brinson *et al.*, 1980)	1105	9.6	1.3	10.4	13.3	6.9	-
Malaysia, Rain forest (Sinun *et al.*, 1992)	3103	-	21.1	411.6	58.7	45.0	0

throughfall in forests in some parts of the world. Net throughfall can be defined as the amount of nutrients picked up from the canopy by precipitation passing through (Vitousek and Sandford Jr., 1986). Amounts as high as 65 kg/ha/year N (Bernhard-Reversat, 1975) and over 400 kg/ha/year K (Sinun *et al.*, 1991) in throughfall have been reported (Table 4.1). Throughfall transports more material to the forest soil than stem flow but stem flow nutrient concentrations are higher (Parker, 1983). Though stem flow contributes less nutrients compared to throughfall (Vitousek and Sandford, 1986), Sinun *et al.*, (1991) report a total of 12.5 kg/ha/year K compared to 14.4 kg/ha/year K in incident precipitation. Table 4.2 shows the percentage contribution of throughfall compared to incident precipitation and litter fall (Bernhard-Reversat, 1975) at a site in Ivory Coast. At this site throughfall contributed significant amounts of N, K, Ca and Mg.

The components of throughfall and stem flow include nutrients leached from the vegetation, nutrients washed from the surface of vegetation and those contained in incident precipitation (Eaton *et al.*, 1973). Some authors however refer to throughfall nutrients as the nutrients derived from the canopy excluding nutrients in incident precipitation (Bernhard-Reversat, 1975; Sinun *et al.*, 1991). The canopy can add or remove nutrients in incident precipitation. Nutrients that have been analyzed by researchers are $NH4^+$-N, NO_3^--N, P, Ca, Mg, K, SO_4^{2-}, Cl^- and H^+ (Parker, 1983). Mineral forms have been the major target but some workers have also measured organic inputs such as organic N (Carlisle *et al.*, 1967; Eaton *et al.*, 1973).

The nutrient content of throughfall and stemflow vary as a result of a number of factors. The tree species and forest structure determine the amount and variability of throughfall and stem flow and thus nutrient fluxes (Vitousek and Denslow, 1986; Sinun *et al.*, 1992). The quantity and timing of precipitation is the major factor determining the amount of material picked from the atmosphere and canopy (Bernhard-Reversat, 1975). Proximity to natural and anthropogenic sources of dust and gas may result in an increase in the amount of material in precipitation. Other factors such as damage of

Table 4.2. Annual amounts of nutrients (%) moved to the forest floor in incident precipitation, throughfall, and litterfall in Ivory Coast. Total is the sum of nutrients in incident precipitation, throughfall, and litterfall (Bernhard-Reversat, 1975).

SITE	Rainfall (mm/yr)	Nutrient source	N	P	K	Ca	Mg
Plateau forest	1400	Incident precipitation (%)	9	14	6	22	4
		Throughfall (%)	25	4	61	15	40
		Litter (%)	66	82	33	63	56
		Total (kg/ha/yr)	258	9.8	85	97	91
Thalweg forest	1800	Incident precipitation (%)	10	6	2	16	4
		Throughfall (%)	26	38	67	21	56
		Litter (%)	64	56	31	63	40
		Total (kg/ha/yr)	246	24	264	135	90

plants due to insect feeding can result in elevated concentrations of nutrients in throughfall and stemflow (Parker, 1983).

4.2.2. Throughfall

Different methods of collecting throughfall water samples have been used. Rain gauges are the most commonly used water sample collection method (Carlisle *et al.*, 1967) and other methods include large water collectors similar to rain gauges (Sinun *et al.*, 1992), narrow mouth bottles (Jordan, 1982), or funnels connected to polyethylene bottles (Carlisle *et al.*, 1967). The location of water sample collectors in the forest can be along transects, randomly distributed (Sinun *et al.*, 1992) and in some cases under selected trees (Eaton *et al.*, 1973). Bruijnzeel (1989) suggests that about 40 rain gauges or collectors in fixed locations are needed to estimate mean throughfall within 10 % confidence limits. The estimate can be improved by random relocation of the collectors at regular intervals (Bruijnzeel, 1989; Sinun *et al.*, 1992). A large number of collectors however can create logistical problems because they result in a large number of samples for analysis, especially when there are many study sites involved. Likewise, random relocation of collectors requires more manpower. Control samples or incident precipitation samples are collected from open areas where there is no canopy. Depending on the size, some workers have highlighted the possibility of contamination with water from the canopy, especially when the control site is located in the middle of the forest or near the forest edge. To avoid contamination, Jordan (1982) used water collectors suspended on 2 m poles above the ground in open areas approximately 100 m from the forest edge. Siting of control sample collectors will depend on whether open areas are available nearby or can be created. Locating control sample collectors far away may result in collection of incident precipitation which is not representative of the study sites and the possibility of equipment being stolen or vandalized. After sampling, volume weighted samples are used for chemical analysis.

4.2.3. Stem flow

Stem flow samples are collected from trees using collars. Different types of collars have been used, such as polyurethane collars sealed with asphalt roofing tar (Jordan, 1978,

Eaton *et al.*, 1973), epoxy resin collars (Sinun *et al.*, 1992) and lead gutter collars sealed with inert plastic or painted with inert bitumastic paint (Carlisle *et al.*, 1967).

Generally a minimum amount of precipitation is required for stem flow to occur. In moist forests in Malaysia Sinun *et al.* (1992) reports a minimum of 1.8 mm of rainfall before stem flow occurs. At this site stem flow was found to be 1.85 % of incident precipitation. Jordan (1978) reports an average of 10 mm in Amazonia (Venezuela) before stem flow occurs and the percentage of rain that becomes stem flow was found to depend on the length and intensity of the storm. Stem flow ranged between 2 and 8 % of rainfall (Jordan, 1978). Bruijnzeel (1989) however found that stem flow in lowland tropical forests ranges between 1 and 2 % of incident rainfall.

Stem flow varies in an irregular manner, with variation being great for different diameter trees and even for trees in the same diameter class (Jordan, 1978). It was found to be unrelated to tree size with large trees only producing higher measurements when there is a high rainfall event (Bruijnzeel, 1989). A number of researchers have reported that small diameter trees have higher stem flow than large diameter trees (Jordan, 1978; Bruijnzeel, 1989). This can be explained in different ways. For instance a small tree surrounded by large trees may have high stem flow because of water dripping from the large trees (Jordan , 1978; Sinun *et al.*, 1992). The other reason could be the branching pattern of the trees, where in small trees branches funnel more water to the stem than larger trees where branches are at angles likely to cause water to drip from branches directly to the ground. Trees also have higher stem flow measurements when they do not have leaves than when they have leaves (Sinun *et al.*, 1992). Stem bark characteristics are also an important factor. Trees with a smooth, dense bark have a higher stem flow than trees with rough corky bark (Gersper and Holowaychuk, 1971).

Incident precipitation adds significant amounts of nutrients to forests and throughfall and stem flow are major pathways for recycling nutrients such as K and Na (Parker, 1983, Bernhard-Reversat, 1975). Despite the importance of nutrient additions in incident precipitation, throughfall and stem flow to nutrient cycling in forests and

woodlands, little research work has been reported in sub-saharan Africa, in miombo woodlands. Most of the research has been confined to moist tropical rain forests in South America (Jordan *et al.,* 1972; Jordan, 1982) and Asia (Sinun *et al.*, 1992) and forests in North America (Gersper and Holowaychuk, 1971; Reiners, 1972; Eaton *et al.*, 1973; Turner and Singer, 1976; Henderson *et al.,* 1977; Westman, 1978; Yawney *et al.*, 1978; Brinson *et al.*, 1980) and Europe (Madgwick and Ovington, 1959, Carlisle *et al.* 1967). There is therefore a need to examine the role of rainfall, throughfall and stem flow in nutrient cycling in southern African woodland and forest ecosystems.

4.3. MATERIALS AND METHODS

4.3.1. Measurement of rainfall and through fall

Water samples were collected from two study sites, Mukuvisi Woodlands and Henderson Research Station. Rainwater samples were collected using 150 mm rain gauges with a diameter of 18 cm. At the Mukuvisi Woodlands, rain gauges were located along 3 transects (described in chapter 3) that cut across the woodland area burnt annually and the area protected from burning. A total of 12, 150 mm rain gauges were placed about 40 m apart along each transect. Six of these were located in the area burnt and the other 6 in the woodland area protected from burning along each transect, making a total of 18 rain gauges in each experiment area. In all, 9 rain gauges were used as a control and were located in areas where there was no vegetation (Figure 4.2).

At Henderson Research Station, rain gauges were also located along transects (described in chapter 3) running through the three experimental areas, the upperslope, midslope and lowerslope. Nine rain gauges were located at about 40 m intervals along each transect, resulting in 3 rain gauges falling into each experimental area (Figure 4.3). A total of 27 rain gauges were used in this area and each experimental area had 9 rain gauges in total. Nine rain gauges were used as control and were placed 40 m apart in the fire guard area where vegetation was cleared.

The amount of rainfall was recorded after each rainfall event. Rain gauges were washed with distilled water after collecting samples to prevent algae from building up, and plant debris in the rain gauge funnel was removed. Some authors recommend the random re-location of rain gauges after collecting water samples (Bruijnzeel, 1989; Sinun *et al.*, 1992). In this study it was not possible because of logistical problems. Each month samples were collected after each rainfall event and immediately frozen before laboratory analysis. During the first month 16 samples were analyzed before and after storage so as to see the effect of storage. Concentration of nutrients showed no detectable changes. Volume-weighted samples were prepared for each month and analyzed for NH_4^+-N, NO_3^--N, pH, Ca, Mg, K and Na. Laboratory analysis was carried out using methods outlined in section 3.2.4.

4.3.2. Measurement of stem flow

Measurement of stem flow was carried out only at Henderson Research Station experiment areas. It would have been preferable to make stem flow measurements at Mukuvisi Woodlands but this was not possible because of management policy restrictions. Two quadrats, 5 m x 5 m were identified randomly in each experiment area on two of the three transects running through the study area. Transects used in each experiment area were randomly selected. Stem flow measurements were taken from trees in the quadrats. Only trees with a diameter greater than 3 cm were measured.

Stem flow samples were collected using plastic (polyethylene) collars tied round tree trunks at a height of about 1.2 m from the ground (Plate 4.1). Sealing was carried out using putty. The putty was in turn covered with an inert silicone sealant to re-inforce the sealing and to prevent stem flow water samples being contaminated with any material from the putty. The collars were attached to 2 L plastic bottles with a tubing (Plate 4.1). Frequent visits were made to check and ensure that the stem flow collars were not leaking. Water samples were collected from each tree after each rainfall event and immediately frozen before laboratory analysis. Sometimes water samples had to be filtered so as to remove soil washed from tree trunks brought up by termites, especially during the first two months. Monthly volume-weighted samples from each tree were

Plate 4.1. Stem flow equipment used at Henderson Research Station experiment sites. A plastic collar was used with a tube attached to drain stem flow water into a 2 L collecting bottle. The picture shows the equipment on a *B. spiciformis* tree.

Figure 4.2: Map at approximate scale of 1cm: 40 m showing rain gauge distribution at Mukuvisi Woodland experiment sites. O – rain gauge inside woodland area and © - rain gauge in open area (control).

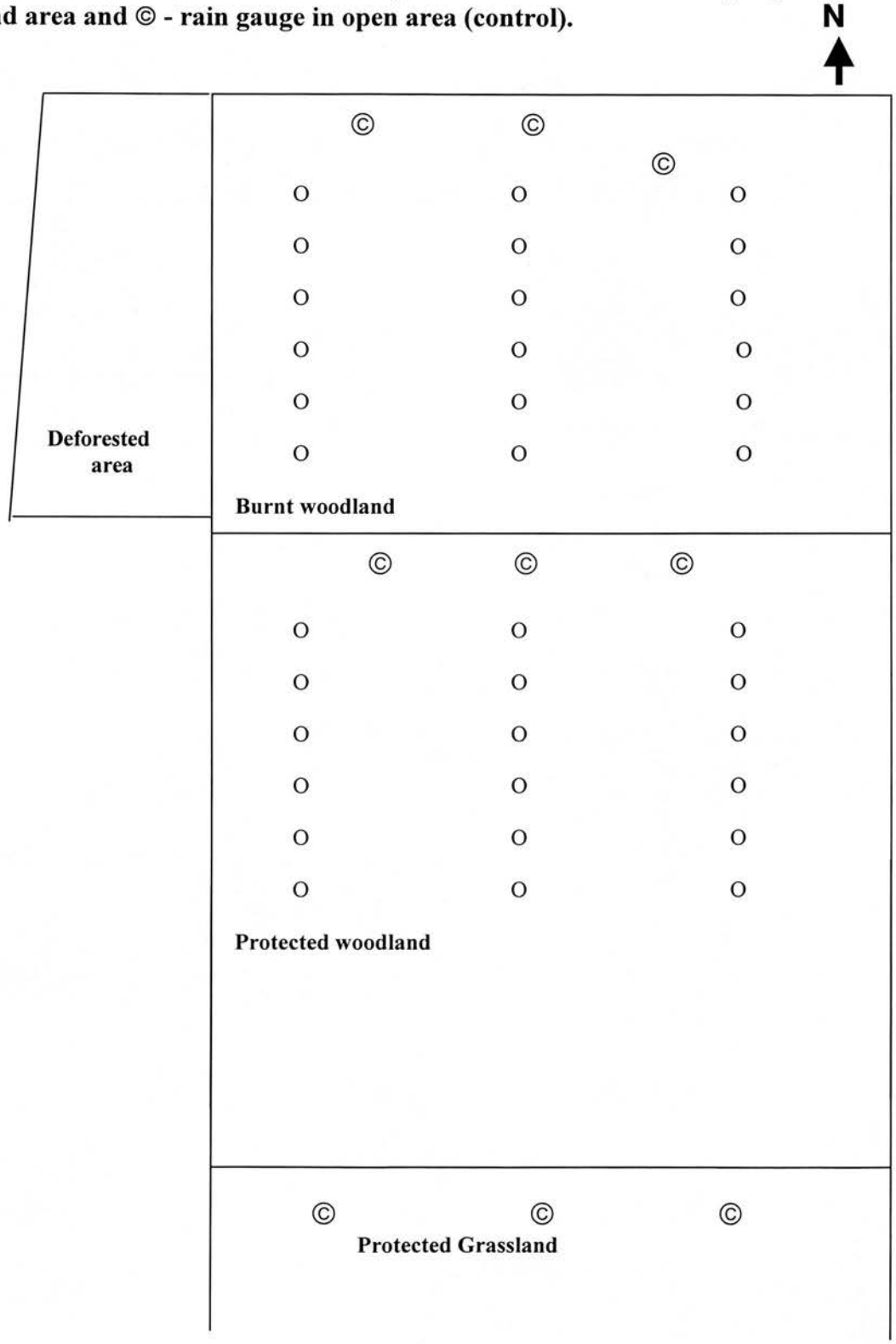
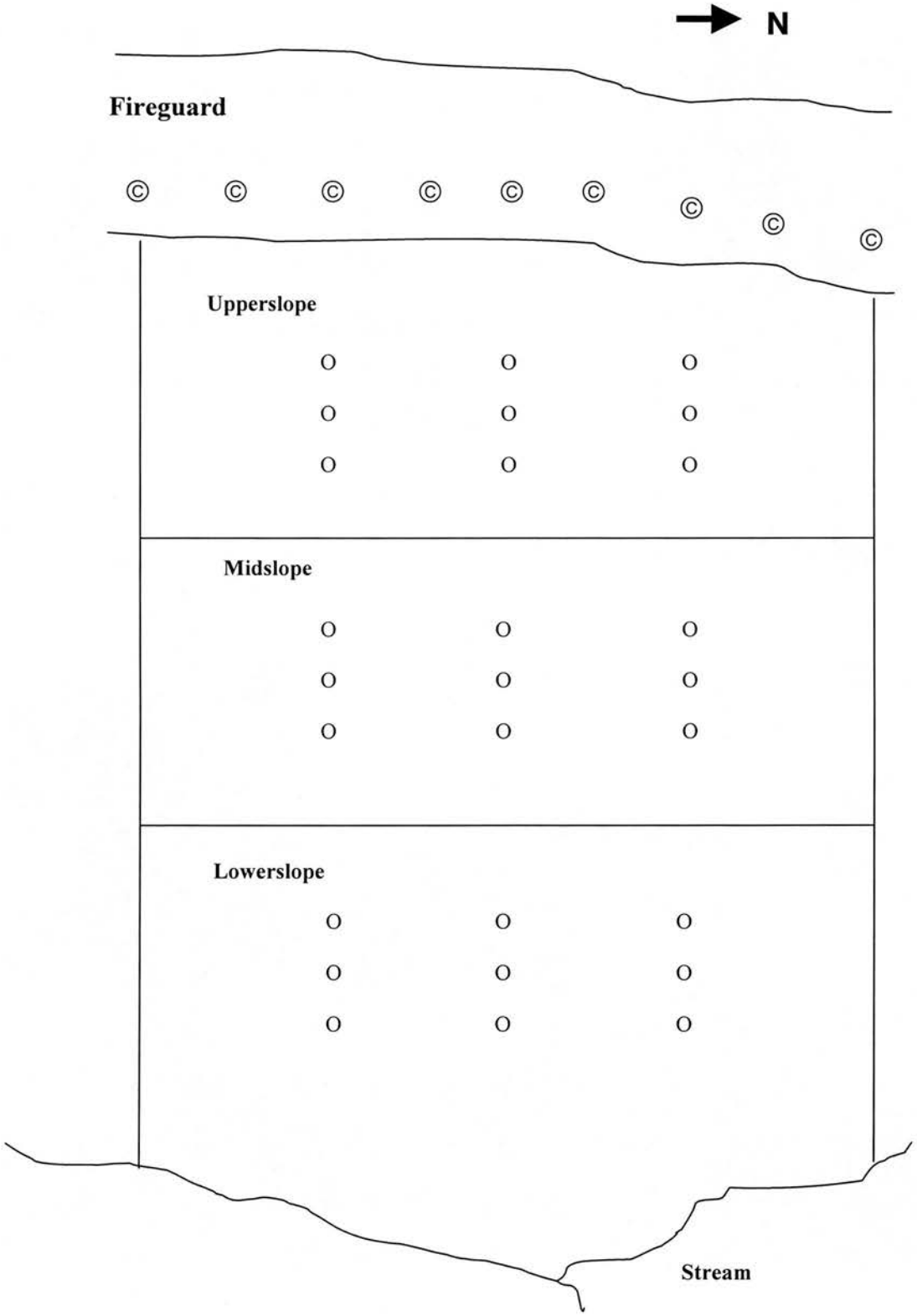


Figure 4.3. Map at an approximate scale of 1cm : 40m showing rain gauge distribution at Henderson Research Station experiment sites. O – rain gauge inside woodland area and © - rain gauge in open area (control).



analyzed for NH_4^+-N, NO_3^--N, pH, Ca, Mg, K and Na each month. Laboratory analysis was carried out using methods outlined in section 2.2.4.

Mean total additions of nutrients in incident precipitation, throughfall and stem flow to the experiment sites at each study site were compared using one-way analysis of variance using Minitab Release 12.1 (MINITAB Inc., 1998). Where the F-test was significant, Fisher's Least Significant Difference (LSD) method was used for pairwise comparison of means to identify pairs with significant differences (Ryan and Joiner, 2001).

4.4. RESULTS AND DISCUSSION

4.4.1. Rainfall, throughfall, stem flow and interception

More rainfall was received at rain gauge height in the control areas where there is no vegetation than in woodland areas at the two study sites. In areas with vegetation, some of the incident precipitation is intercepted by trees (Parker, 1983). Some of the intercepted rain later falls through the canopy and is measured either as throughfall or stem flow. The rest of the intercepted water is lost through evaporation (Parker, 1983; Bruijnzeel, 1989).

The duration of 1999/2000-rainfall season was from October 1999 to June 2000 for both study sites (Figure 4.3 & 4.4). This was much longer than the 2000/2001 rain season which was from October 2000 to March 2001 and November 2000 to April 2001 for Henderson Research Station and Mukuvisi Woodlands respectively. The rain season in both study areas is normally from mid to late October to the end of March or early April. Despite the difference in the length of the rain season, the 1999/2000 season received only 11.2 mm more than the 2000/2001 season at Mukuvisi Woodlands. At the same site, there was a mid season drought in January of the 2000/2001 rain season. At Henderson Research Station, 162.3 mm more were received during the 1999/2000 season than the 2000/2001 season. Length of rain season can affect the amount of

Table 4.3. Total rainfall (mm/yr), % throughfall, % stem flow and % interception at Mukuvisi Woodlands and Henderson Research Station experiment sites. % throughfall, % stem flow and % interception is throughfall, stem flow and interception expressed as percent of rainfall received. At Mukuvisi Woodlands sites stem flow was not measured (n.m. –not measured and ♣ - % interception includes stem flow; ♦ - rainfall in mm/yr).

Site	Season	Rainfall/ Through-fall (mm/yr)	Throughfall (%)	Stem flow (%)	Interception (%)
Muk-Prot	1999/2000	969.6	82.2	n.m.	17.8♣
	2000/2001	944.5	85.9	n.m.	14.1♣
Muk-Burn	1999/2000	1082.2	91.6	n.m.	8.4♣
	2000/2001	966.2	88.1	n.m.	11.9♣
Muk-Con	1999/2000	1180.5♦			
	2000/2001	1169.3♦			
Hen-Up	1999/2000	977.1	96.0	0.3	3.7
	2000/2001	806.8	94.3	0.3	5.4
Hen-Mid	1999/2000	953.0	93.7	0.4	5.9
	2000/2001	729.9	85.3	0.4	14.3
Hen-Low	1999/2000	846.6	83.2	0.4	16.4
	2000/2001	745.2	87.1	0.4	12.5
Hen-Con	1999/2000	1017.7♦			
	2000/2001	855.4♦			
Statistical Significance		***			

*** Highly significant difference columnwise (in amount of rainfall/throughfall) at $p<0.001$ ($F_{13, 148} = 1.79$)

nutrients added to the woodlands in incident rainfall, throughfall and stem flow. A long rain season is likely to result in more nutrient additions. Even when the rainfall is the same it would be expected that during a long rain season there will be more aerosol deposits on vegetation surfaces which will be washed from the canopy as either throughfall or stem flow.

The amount of rainfall intercepted by tree depends on the canopy cover and density. In this study canopy cover was not measured, only basal area was measured (Chapter 3.). Interception of rainfall at Mukuvisi Woodlands was higher in the Muk-Prot experiment site than Muk-Burnt for both seasons (Table 4.3). At Mukuvisi Woodlands Muk-Prot (20.6 m^2/ha) had a higher basal area compared to Muk-Burn (13.5 m^2/ha) and a higher interception. It can be inferred from these results that Muk-Prot had a higher canopy cover than Muk-Burn. At Henderson Research Station experiment areas, Hen-Up (12.9 m^2/ha) had the lowest basal area and also had the lowest interception during both 1999/2000 and 2000/2001 rain seasons. Hen-Mid (19.4 m^2/ha) and Hen-Low (20.8 m^2/ha) had similar basal areas which were not significantly different ($p<0.05$). It is therefore possible that at Henderson, Hen-Up had the lowest canopy cover whereas Hen-Mid and Hen-Low have almost similar canopy cover. This probably explains why in one season Hen-Mid had higher interception and Hen-Low was higher in the other season.

Throughfall was however higher in Muk-Burn than Muk-Prot. Mukuvisi experiment sites had a throughfall of 82.2 (Muk-Prot) and 91.6 % (Muk-Burn) of the rainfall received in the 1999/2000 rain season and 85.9 (Muk-Prot) and 88.1 % (Muk-Burn) of the rainfall received for the 2000/2001 rain season. Muk-Burn which had less vegetation cover compared to Muk-Prot had lower interception and higher throughfall. At Henderson Research Station, Hen-Low had the highest interception with the exception of the 2000/2001 season where Hen-Mid had the highest (Table 4.3). For both seasons Hen-Up had the lowest interception. Throughfall at Henderson was highest at Hen-Up and lowest at Hen-Low with the exception of the 2000/2001 season when

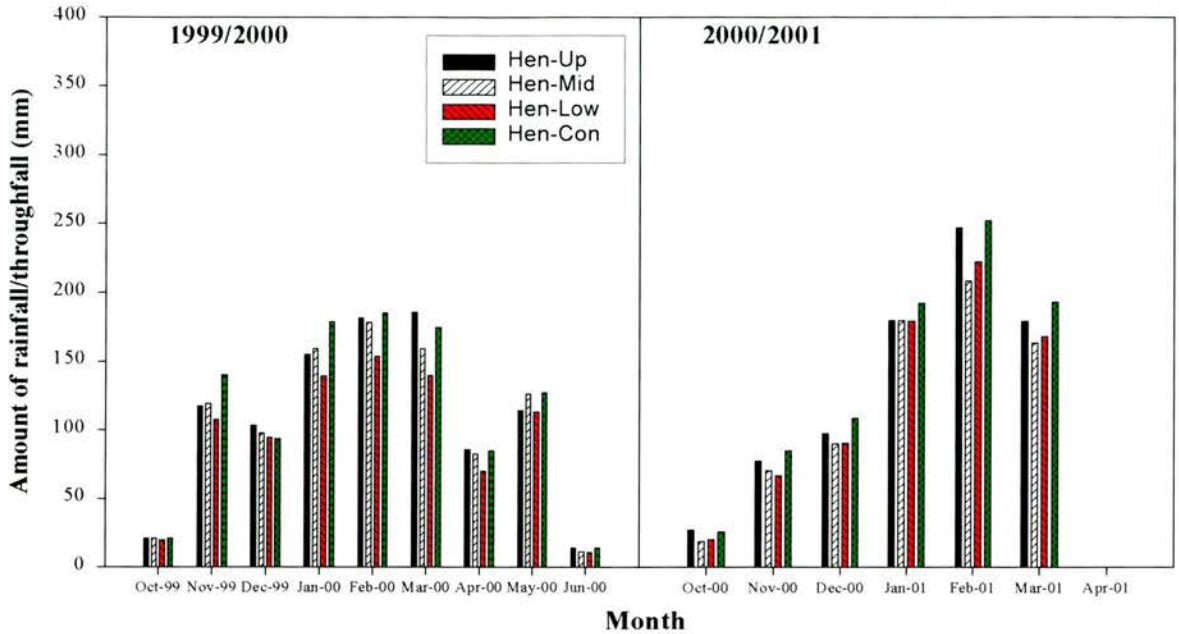


Figure 4.4. Amount of rainfall (mm) received at Hen-Con and throughfall (mm) received at Hen-Up, Hen-Mid and Hen-Low experimental sites in the 1999/2000 and 2000/2001 rain seasons.

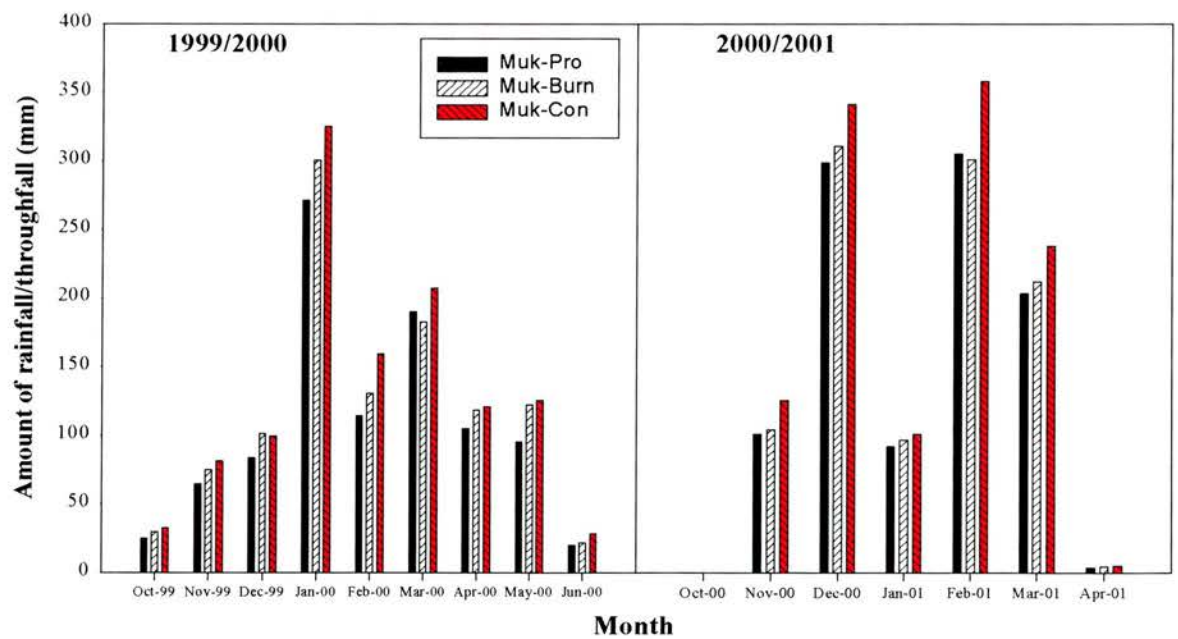


Figure 4.5. Amount of rainfall (mm) received at Muk-Con and throughfall (mm) received at Muk-Prot and Muk-Burn experimental sites in the 1999/2000 and 2000/2001 rain seasons.

Table 4.4. Height and diameter (at 120 cm height or dbh) of trees used to measure stem flow at the experiment sites at Henderson Research Station. The same trees were used for stem flow measurement for both the1999/2000 and 2000/2001 rain seasons.

SPECIES	HEN-UP		HEN-MID		HEN-LOW	
	Height (m)	dbh (cm)	Height (m)	dbh (cm)	Height (m)	dbh (cm)
B. boehmii	6.8	9.0	3.7	3.3	3.5	5.0
	3.9	4.5	4.6	6.0	5.5	6.0
			7.0	10.0	6.0	9.4
			11.2	26.0	9.5	16.4
					12.0	34.7
B. spiciformis	7.5	11.6	9.3	12.7	5.5	6.4
	8.0	6.0	10.6	15.0	6.3	4.7
	8.7	16.0	11.8	28.5	8.6	10.0
					12.2	35.0
J. globiflora	3.7	4.0	3.0	3.2	♣	
	5.1	5.0	5.0	5.7		
	7.5	12.0	8.7	8.3		
			9.2	16.6		

♣ - Tree species not present at this experiment area.

Hen-mid had the lowest throughfall. The Henderson sites had 83.2 to 96.0 % and 85.3 to 94.3 % for the 1999/2000 and 2000/2001 rain seasons respectively (Table 4.3). The highest throughfall at Henderson was measured at Hen-Up that had fewer trees than the other two sites lower downslope.

Stem flow measured at Henderson was less than 1% of total rainfall received in the study area (Table 4.3). Other studies have shown that stem flow measured in forests is very low. Sinum *et al.*, (1992) reports a stem flow of 1.85 % of the total rainfall received in a Malaysian rain forest. Jordan (1978) found stem flow of a similar magnitude in a Venezuelan Amazon rain forest and Eaton *et al.*, (1973) reports a stem flow of less than 5 % of the total rainfall received in northern hardwood forest.

However, at Henderson the amount of stem flow was lower possibly because either the amount of rainfall and/or the tree density is lower at these forest sites. Measurements in the two quadrats in each experiment site were pooled together and treated as being from one quadrat 50 m^2 in area. Only three tree species, *B. boehmii, B. spiciformis* and *J. globiflora* were found in the quadrats used for stem flow measurements in Hen-Up and Hen-Mid (Table 4.4). In Hen-Low quadrats two tree species, *B. boehmii,* and *B. spiciformis* were present. Hen-Mid had the highest stem flow, followed by Hen-Low with Hen-Up having the lowest (Table 4.12 & 4.13). There were more trees in the quadrats in Hen-Mid compared to the other two experiment sites (Table 4.4). Hen-Low had the lowest number of trees in the quadrats. The differences in stem flow could be explained by the number of trees in quadrats in each experiment sites. The higher the number of trees in the quadrat the higher was the stem flow measured.

4.4.2. Nutrients added in incident rainfall and throughfall

The mean monthly nutrient concentrations (Table 4.5-8) in rainfall and throughfall were highest in the first month of both rain seasons. After the first month the concentration of nutrients decreased substantially. High nutrient concentrations are expected at the beginning of the rain season because of the high amount of dust and other particles in the air and also on tree surfaces (Jonnalagadda *et al.*, 1994). As the season progresses,

there is less dust. Nutrients added in the 1999/2000 season were higher than in the 2000/2001 season. Differences in nutrients added may be due to the difference in length of the rainy season. The 1999/2000 season was longer by at least 3 months and thus nutrients were picked up from the air and tree surfaces over a longer period. This season extended to May and June a period when senescence and litterfall increases significantly. It has been observed that during the period prior to senescence more cations are leached from the canopy increasing the amount of nutrients in throughfall (Gosz *et al.*, 1969; Eaton *et al.*, 1973).

The nutrients measured in throughfall water samples included those in incident precipitation and nutrients from the miombo woodland canopy. Ammonium-N added in rainfall (control) at Mukuvisi and at Henderson in the 1999/2000 rain season (Figure 4.6) was of similar magnitude and amounted to 694.9 mg/m^2 and 628.4 mg/m^2 respectively. This amount is high compared to some tropical forests receiving higher amounts of rainfall (Table 4.1) (Nye, 1961; Bruijnzeel; 1989).

The highest additions of NH_4^+-N in throughfall for the two study sites were at Muk-Burn (785.3 mg/m^2) and the lowest was at Hen-Up (543.9 mg/m^2). In the 2000/2001 season (Figure 4.7), Muk-Prot (563.0 mg/m^2) had the highest NH_4^+-N additions and Hen-Con (291.8 mg/m^2) had the lowest. Nitrate-N added in rainfall and throughfall in the 1999/2000 season showed a similar trend as ammonium-N in the same season, with Muk-Burn (780.5 mg/m^2) having received the highest addition and Hen-Up (565.6 mg/m^2) the lowest (Figure 4.8). In the 2000/2001 season Muk-Prot had the highest addition of 563.0 mg/m^2 and Hen-Con had the lowest of 279.3 mg/m^2 (Figure 4.9). Higher additions at Mukuvisi Woodlands sites could be explained by the proximity of the site to an urban industrial area where pollution is relatively high (Jonnalagadda *et al.*, 1991).

Table 4.5. Mean monthly nutrient concentrations (mg/l) in rainfall and throughfall water samples from Mukuvisi Woodlands experiment sites in the 1999/2000 season. Muk-Con results are for rainfall received at an open area without vegetation. Muk-Prot and Muk-Burn are results for rainfall + throughfall within miombo woodland.

Muk-Prot

Month	Oct. 1999	Nov. 1999	Dec. 1999	Jan. 2000	Feb. 2000	Mar. 2000	Apr. 2000	May. 2000	Jun. 2000
Throughfall (mm)	25.1	64.6	83.3	271.7	114.3	190.3	105.1	95.2	19.9
pH	6.05	6.35	6.3	6.4	5.98	6	6.02	5.86	5.94
NH_4^+-N (mg/l)	5.48	0.55	0.64	0.46	0.67	0.61	0.55	0.56	0.56
NO_3^-N (mg/l)	6.05	0.61	0.63	0.58	0.61	0.61	0.62	0.59	0.61
Ca (mg/l)	6.75	3.96	4.31	3.6	0.86	0.92	0.97	1.6	1.29
Mg (mg/l)	1.23	0.82	0.87	0.76	0.18	0.21	0.23	0.33	0.28
K (mg/l)	6.84	6.04	6.16	5.92	2.28	1.81	1.34	1.5	1.42
Na (mg/l)	2.4	1.91	2.14	1.67	0.34	0.28	0.22	0.37	0.3
Muk-Burnt									
Throughfall (mm)	29.7	74.6	101.2	300.8	130.4	182.6	118.4	122.3	21.9
pH	6.01	6.3	6.2	6.4	5.93	5.87	5.81	5.6	5.71
NH_4^+-N (mg/l)	5.34	0.57	0.63	0.51	0.65	0.67	0.70	0.52	0.61
NO_3^-N (mg/l)	5.25	0.57	0.59	0.55	0.68	0.69	0.70	0.58	0.64
Ca (mg/l)	7.8	3.3	3.33	3.26	2.02	1.65	1.27	1.71	1.49
Mg (mg/l)	1.28	0.83	0.9	0.75	0.22	0.22	0.22	0.23	0.23
K (mg/l)	7.65	5.06	5.9	4.22	1.56	1.47	1.37	1.7	1.54
Na (mg/l)	2.33	1.49	1.96	1.02	0.34	0.26	0.17	0.32	0.25
Muk-Con									
Rainfall (mm)	32.7	81.2	99.3	325.7	159.3	207.5	121	125.5	28.3
pH	5.53	6.15	6.1	6.2	5.87	5.5	5.13	5.2	5.17
NH_4^+-N (mg/l)	4.01	0.38	0.36	0.40	0.64	0.57	0.50	0.56	0.53
NO_3^-N (mg/l)	5.06	0.51	0.50	0.52	0.58	0.55	0.52	0.56	0.54
Ca (mg/l)	1.56	1.69	1.86	1.52	1.69	1.2	0.71	0.92	0.82
Mg (mg/l)	0.13	0.21	0.22	0.19	0.14	0.07	0	0.12	0.06
K (mg/l)	0.58	1.25	1.47	1.02	0.27	0.28	0.28	0.32	0.3
Na (mg/l)	0.51	0.9	0.93	0.87	0.44	0.34	0.23	0.28	0.26

Table 4.6. Mean monthly nutrient concentrations (mg/l) in rainfall and throughfall water samples from Mukuvisi Woodlands experiment sites in the 2000/2001 season. Muk-Con results are for rainfall received at an open area without vegetation. Muk-Prot and Muk-Burn are results for rainfall + throughfall within miombo woodlands.

Muk-Prot						
Month	Nov 2000	Dec 2000	Jan 2001	Feb 2001	Mar 2001	Apr 2001
Throughfall (mm)	101	298.8	91.9	305.3	203.7	3.7
pH	6	5.9	5.99	6.1	5.8	6.2
NH_4^+-N (mg/l)	1.41	0.3	0.46	0.53	0.61	0.71
NO_3^-N (mg/l)	1.11	0.88	0.3	0.4	0.41	0.63
Ca (mg/l)	2.95	0.42	1.02	0.24	0.71	0.97
Mg (mg/l)	1.01	0.07	0.11	0.06	0.09	0.08
K (mg/l)	2.79	0.27	1.12	0.67	1.11	1.13
Na (mg/l)	0.87	0.17	0.3	0.2	0.11	0.09
Muk-Burnt						
Throughfall (mm)	104.2	311	96.5	301.5	212.1	4.7
pH	6.1	6	6.01	5.88	5.9	6.2
NH_4^+-N (mg/l)	1.29	0.11	0.3	0.37	0.46	0.58
NO_3^-N (mg/l)	1.32	0.09	0.26	0.4	0.38	0.55
Ca (mg/l)	3.01	0.51	1.13	0.4	0.99	1.09
Mg (mg/l)	1.11	0.09	0.14	0.04	0.13	0.09
K (mg/l)	3.15	0.41	2.14	1.07	1.21	1.42
Na (mg/l)	0.71	0.1	0.36	0.33	0.19	0.18
Muk-Con						
Rainfall (mm)	125.5	341.8	100.7	358	238.3	5.0
pH	6.15	5.8	6.1	5.7	5.99	6.01
NH_4^+-N (mg/l)	1.13	0.21	0.31	0.29	0.35	0.5
NO_3^-N (mg/l)	0.92	0.3	0.2	0.09	0.17	0.29
Ca (mg/l)	1.01	0.78	0.86	0.22	0.59	0.75
Mg (mg/l)	0.1	0.11	0.06	0.02	0.07	0.05
K (mg/l)	0.88	0.33	0.81	0.71	0.89	0.78
Na (mg/l)	0.21	0.09	0.13	0.3	0.08	0.09

Table 4.7. Mean monthly nutrient concentrations (mg/l) in rainfall and throughfall water samples from Henderson experiment sites in the 1999/2000 season. Hen-Con results are for rainfall received at an open area without vegetation. Hen-Up, Hen-Mid and Hen-Low are results for rainfall + throughfall within miombo woodlands. (Thr'fall – Throughfall)

Hen-Up									
Month	Oct. 1999	Nov. 1999	Dec. 1999	Jan. 2000	Feb. 2000	Mar. 2000	Apr. 2000	May. 2000	Jun. 2000
Thr'fall (mm)	21.1	117.1	103.3	154.7	181.5	185.8	85.6	113.9	14.1
pH	5.87	5.68	5.89	5.99	5.99	5.97	5.6	5.62	5.56
NH_4^+-N (mg/l)	1.02	0.81	0.45	0.5	0.61	0.49	0.49	0.46	0.54
NO_3^-N (mg/l)	1.45	1.38	0.44	0.47	0.45	0.43	0.39	0.48	0.4
Ca (mg/l)	0.41	0.3	0.34	0.48	0.75	0.52	0.65	0.1	0.36
Mg (mg/l)	0.18	0.16	0.16	0.17	0.09	0.13	0.11	0.02	0.07
K (mg/l)	1.01	0.87	0.87	0.92	0.3	0.61	0.48	0.52	0.49
Na (mg/l)	0.35	0.27	0.3	0.24	0.01	0.13	0.08	0.07	0.06
Hen-Mid									
Thr'fall (mm)	20.7	119.2	97.7	159.1	178	158.9	82.4	125.8	11.3
pH	5.99	5.89	5.93	5.97	6.01	6.02	5.99	5.9	5.78
NH_4^+-N (mg/l)	1.03	0.81	0.45	0.59	0.53	0.56	0.64	0.5	0.53
NO_3^-N (mg/l)	1.47	1.39	0.48	0.48	0.47	0.39	0.44	0.5	0.46
Ca (mg/l)	0.38	0.34	0.43	0.37	0.88	0.58	0.67	0.08	0.37
Mg (mg/l)	0.18	0.19	0.21	0.2	0.15	0.16	0.12	0.03	0.07
K (mg/l)	1.12	1.06	1.01	1.12	0.31	0.75	0.47	0.64	0.63
Na (mg/l)	0.41	0.34	0.29	0.34	0.02	0.16	0.08	0.07	0.06
Hen-Low									
Thr'fall (mm)	19.7	107.3	94.2	139	153.4	139.7	69.8	112.9	10.6
pH	6.1	5.99	6.03	6.06	6.14	6.1	6.12	5.72	5.92
NH_4^+-N (mg/l)	1.34	1.06	0.60	0.60	0.78	0.69	0.73	0.64	0.69
NO_3^-N (mg/l)	1.91	1.81	0.61	0.62	0.62	0.62	0.62	0.57	0.60
Ca (mg/l)	0.59	0.49	0.58	0.6	1.13	0.87	1.00	0.12	0.56
Mg (mg/l)	0.24	0.21	0.22	0.23	0.12	0.18	0.15	0.03	0.09
K (mg/l)	1.32	1.17	1.18	1.24	0.4	0.82	0.61	0.7	0.66
Na (mg/l)	0.40	0.37	0.38	0.33	0.02	0.18	0.10	0.07	0.08
Hen-Con									
Rainfall (mm)	21	140	93.5	178.4	185	174.4	84.8	126.8	13.8
pH	5.57	5.57	5.83	5.65	5.45	5.55	5.5	5.42	5.46
NH_4^+-N (mg/l)	0.74	0.60	0.55	0.56	0.69	0.62	0.66	0.61	0.63
NO_3^-N (mg/l)	0.96	0.60	0.58	0.54	0.62	0.58	0.60	0.53	0.57
Ca (mg/l)	0.10	0.02	0.03	0.04	0.22	0.13	0.18	0.09	0.13
Mg (mg/l)	0.05	0.05	0.01	0.02	0.01	0.02	0.01	0.01	0.01
K (mg/l)	0.23	0.13	0.17	0.21	0.04	0.13	0.08	0.04	0.06
Na (mg/l)	0.07	0.05	0.03	0.04	0.01	0.03	0.02	0.01	0.01

Table 4.8. Mean monthly nutrient concentrations (mg/l) in rainfall and throughfall water samples from Henderson experiment sites in the 2000/2001 season. Hen-Con results are for rainfall received at an open area without vegetation. Hen-Up, Hen-Mid and Hen-Low are results for rainfall + throughfall within miombo woodlands. (Thr'fall – Throughfall)

Hen-Up						
Month	Oct. 2000	Nov. 2000	Dec. 2000	Jan. 2001	Feb. 2001	Mar. 2001
Thr'fall (mm)	26.8	77	97.2	179.7	247	179.1
pH	6.05	6.1	6	6.25	6.3	6.2
NH_4^+-N (mg/l)	1.11	0.4	0.38	0.3	0.31	0.4
NO_3^-N (mg/l)	1.08	0.49	0.38	0.29	0.29	0.3
Ca (mg/l)	0.70	0.35	0.5	0.67	0.61	0.37
Mg (mg/l)	0.21	0.07	0.08	0.09	0.01	0.04
K (mg/l)	1.14	0.89	0.91	0.7	0.49	0.59
Na (mg/l)	0.23	0.1	0.15	0.1	0.07	0.05
Hen-Mid						
Thr'fall (mm)	18.8	70.3	89.9	179.3	208.4	163.2
pH	6.10	6.00	6.10	6.20	6.20	5.99
NH_4^+-N (mg/l)	1.33	0.41	0.47	0.46	0.38	0.4
NO_3^-N (mg/l)	1.21	0.79	0.41	0.4	0.36	0.27
Ca (mg/l)	0.68	0.4	0.55	0.71	0.63	0.41
Mg (mg/l)	0.2	0.07	0.09	0.09	0.02	0.07
K (mg/l)	1.35	0.95	0.95	0.61	0.63	0.64
Na (mg/l)	0.31	0.11	0.2	0.1	0.07	0.09
Hen-Low						
Thr'fall (mm)	19.8	66.4	90	179.2	222.1	167.7
pH	6.05	5.99	6.04	6.18	6.2	6
NH_4^+-N (mg/l)	1.40	0.41	0.53	0.46	0.43	0.49
NO_3^-N (mg/l)	1.23	0.98	0.38	0.48	0.39	0.43
Ca (mg/l)	0.72	0.38	0.6	0.69	0.72	0.49
Mg (mg/l)	0.16	0.08	0.1	0.09	0.03	0.07
K (mg/l)	1.41	1.01	0.92	0.7	0.61	0.68
Na (mg/l)	0.29	0.15	0.2	0.12	0.09	0.1
Hen-Con						
Thr'fall (mm)	25.3	84.5	108.3	192	252.3	193
pH	6.10	6.00	5.99	6.30	6.30	6.20
NH_4^+-N (mg/l)	0.63	0.41	0.36	0.29	0.29	0.38
NO_3^-N (mg/l)	0.78	0.37	0.36	0.29	0.30	0.30
Ca (mg/l)	0.15	0.08	0.05	0.12	0.13	0.11
Mg (mg/l)	0.04	0.06	0.02	0.02	0.01	0.01
K (mg/l)	0.30	0.11	0.18	0.23	0.09	0.08
Na (mg/l)	0.08	0.05	0.02	0.04	0.01	0.01

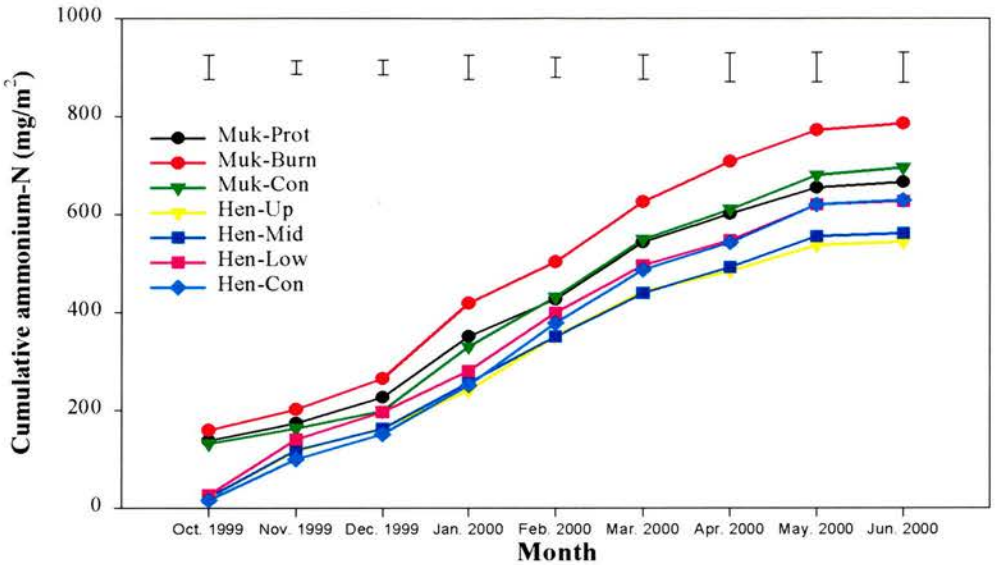


Figure 4.6. Cumulative ammonium-N added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Cumulative NH_4^+-N increased almost linearly with time (bars represent standard errors of means, n = 7).

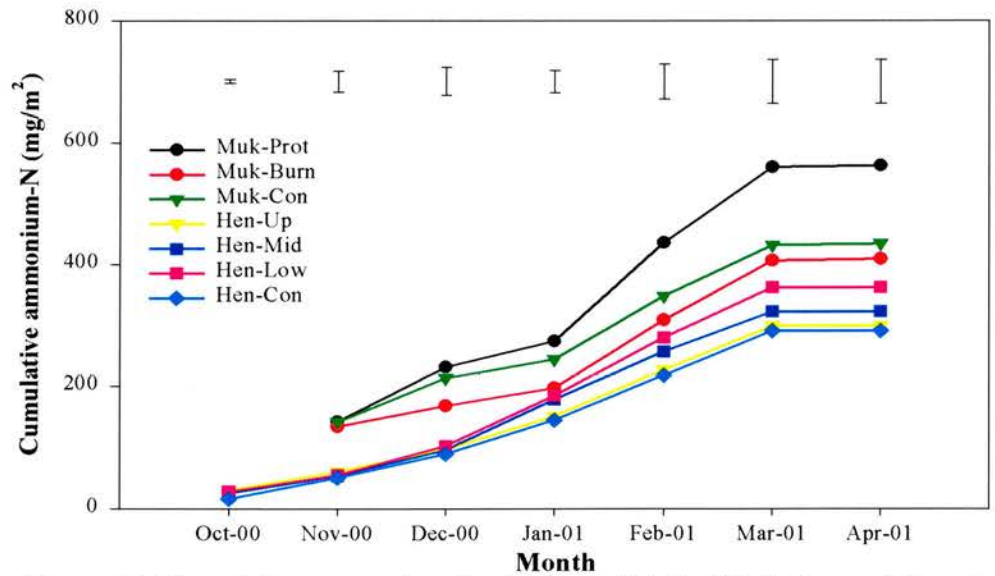


Figure 4.7. Cumulative ammonium-N added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. There was a sharp increase in NH_4^+-N from January 2001 at Mukuvisi sites attributable to a high amount of rainfall received during this month. At Henderson, the pattern was similar to that in 1999/2000 rain season (bars represent standard errors of the means, n = 7)

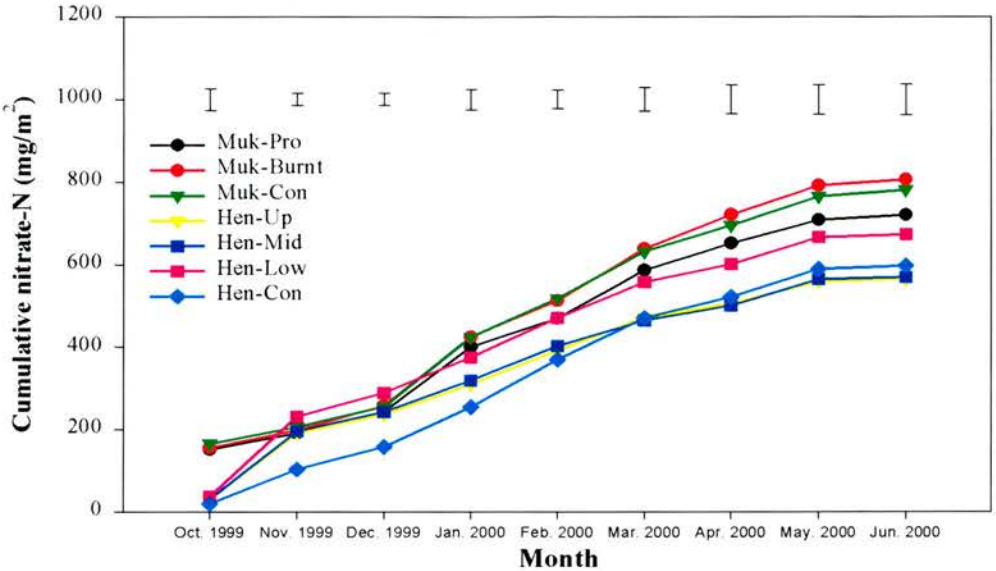


Figure 4.8. Cumulative nitrate-N added in rainfall at Muk-Con and Hen-Con and Throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Cumulative NO_3^--N increased almost linearly with time (bars represent standard errors of means, n = 7).

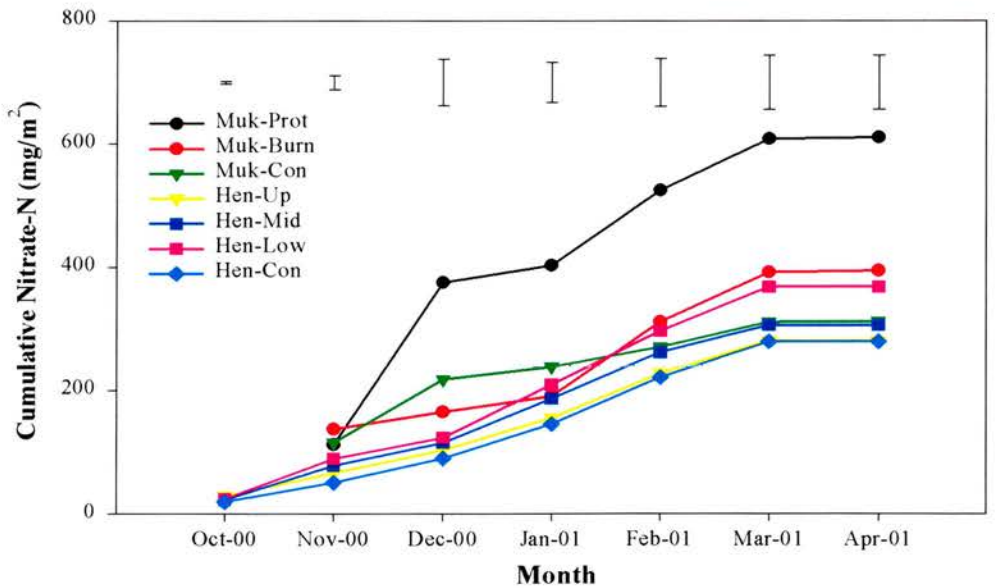


Figure 4.9. Cumulative nitrate-N added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. Muk-Prot, the experimental area with the highest tree density showed a higher increase in cumulative NO_3^--N. The other sites had a similar pattern (bars represent standard errors of the means, n = 7).

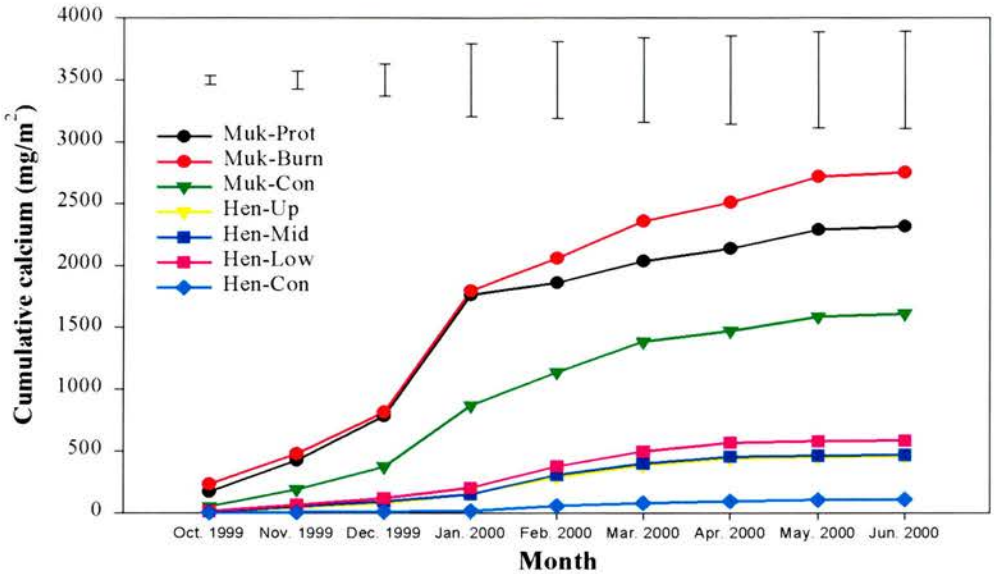


Figure 4.10. Cumulative Ca added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Mukuvisi experimental sites had higher Ca in rainfall and throughfall than Henderson sites (bars represent standard errors of the means, n = 7).

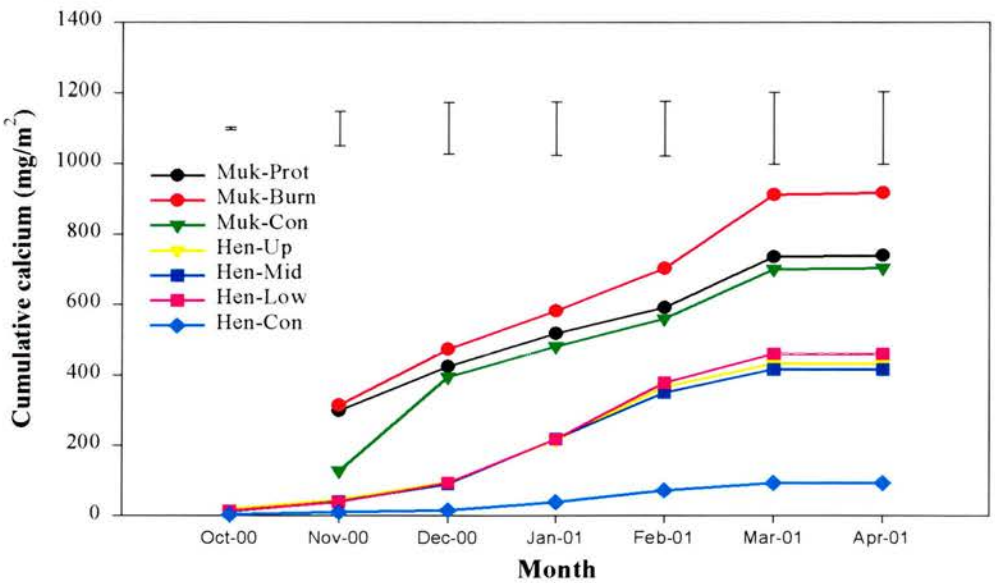


Figure 4.11. Cumulative Ca added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. The order and pattern of cumulative Ca is similar to but lower than the 1999/2000 rain season with Muk-Burn having the highest amount (bars represent standard errors of the means, n = 7).

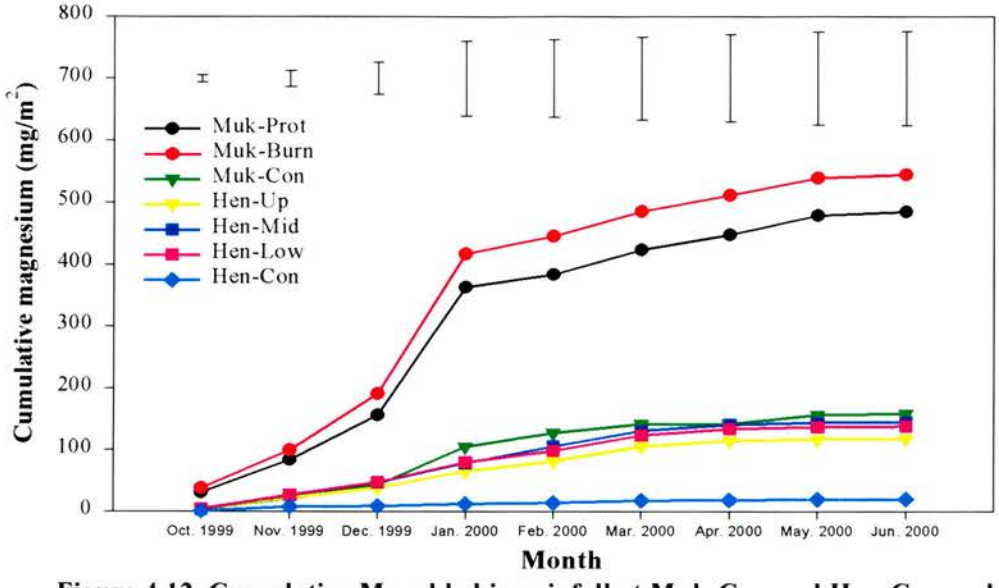


Figure 4.12. Cumulative Mg added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Cumulative Mg was highest at Muk-Burn and Muk-Prot, a similar trend observed for Ca (bars represent standard errors of the means, n = 7).

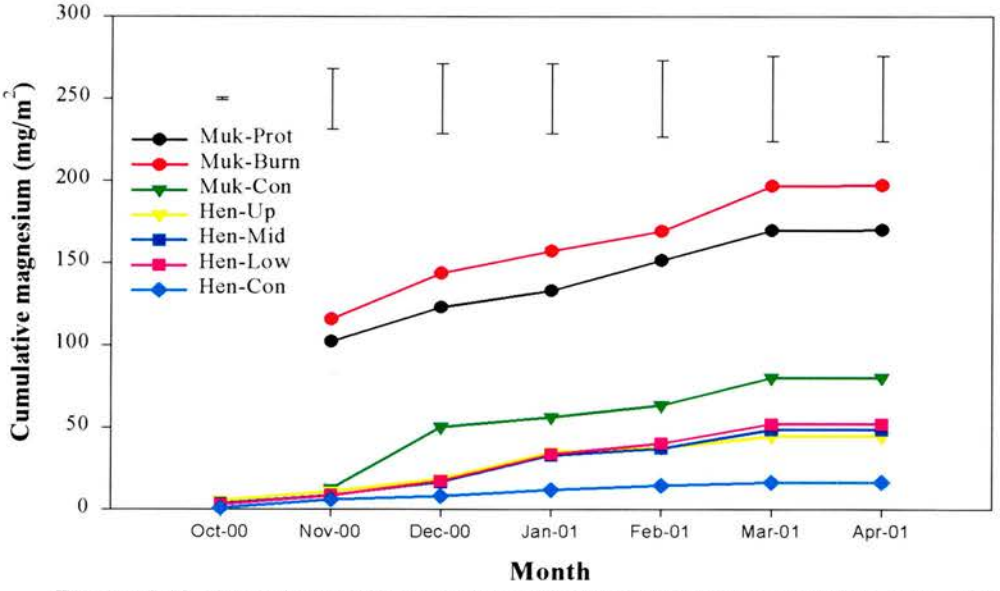


Figure 4.13. Cumulative Mg added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. Experimental sites showed a similar trend as in the 1999/2000 rain season but overall, nutrients were about 50 % of amounts in previous rain season (bars represent standard errors of the means, n = 7).

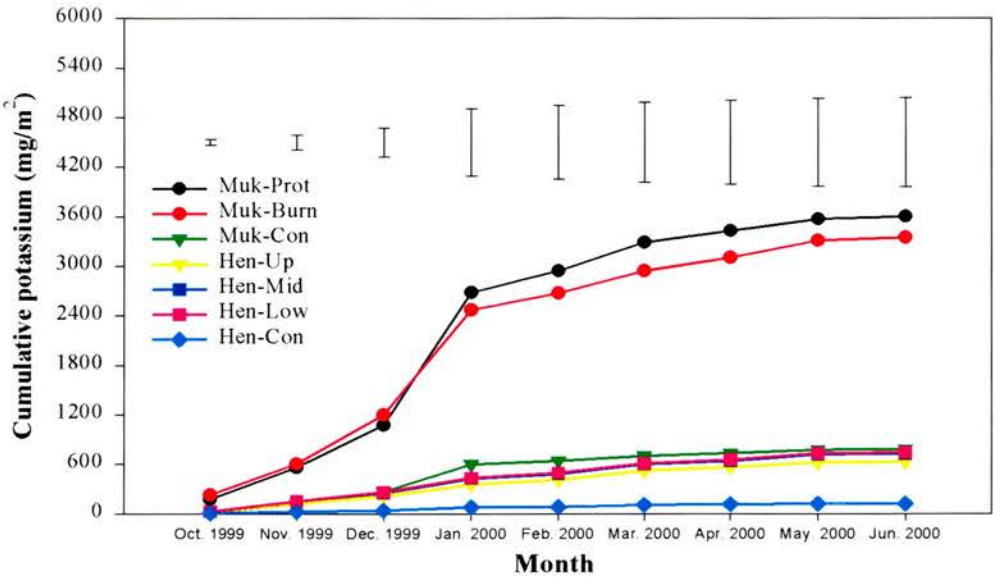


Figure 4.14. Cumulative K added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Cumulative K was the highest cation in rainfall and throughfall compared to the other cations and had a similar trend to Mg in 1999/2000 rain season but with Muk-Prot having higher K than Muk-Burn (bars represent standard errors of the means, n = 7).

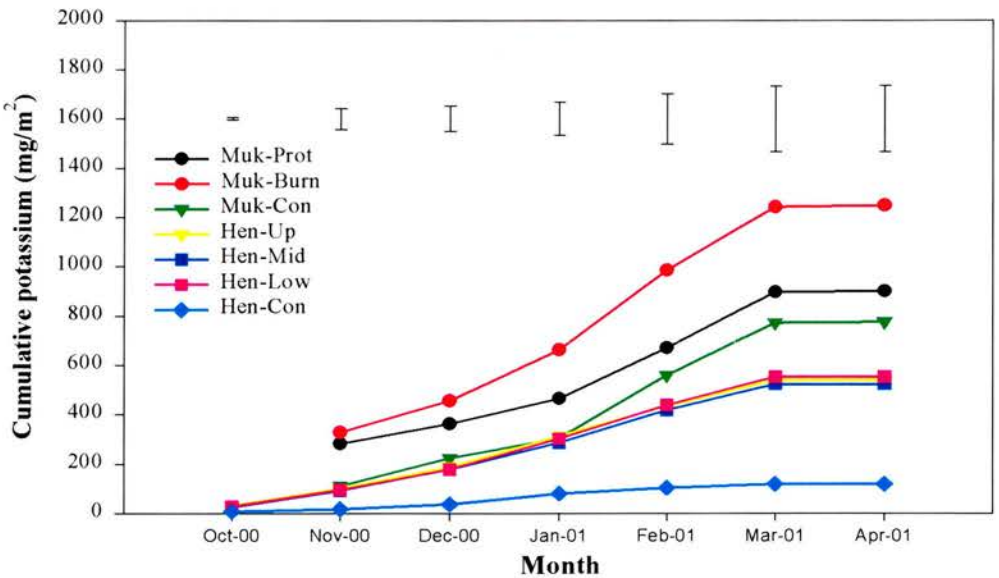


Figure 4.15. Cumulative potassium added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. K at Mukuvisi sites in this season was slightly less than 50 % of 1999/2000 rain season (bars represent standard errors of the means, n = 7).

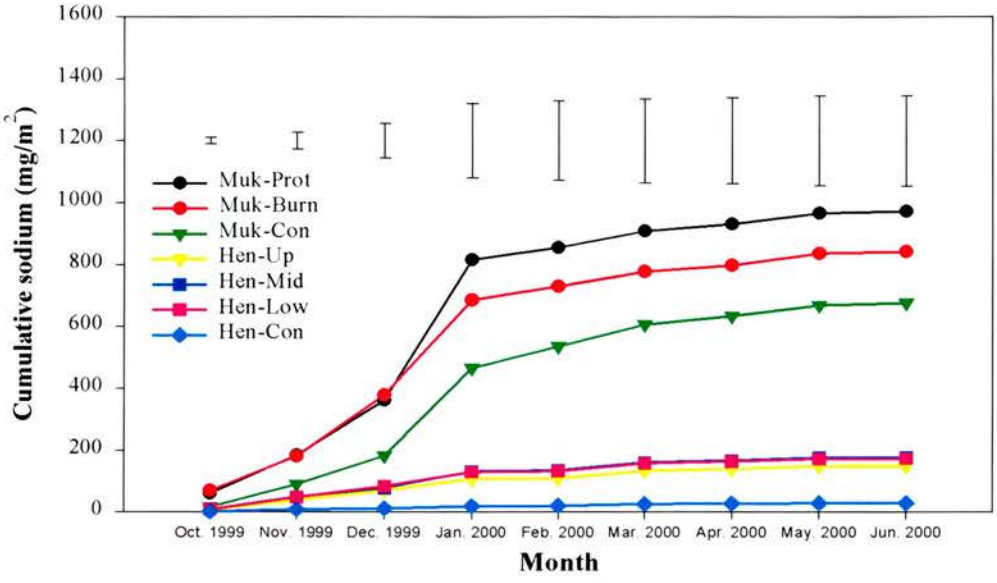


Figure 4.16. Cumulative sodium added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 1999/2000 rain season. Mukuvisi experimental sites had higher Na in rainfall and throughfall than Henderson Research Station sites (bars represent standard errors of the means, n = 7).

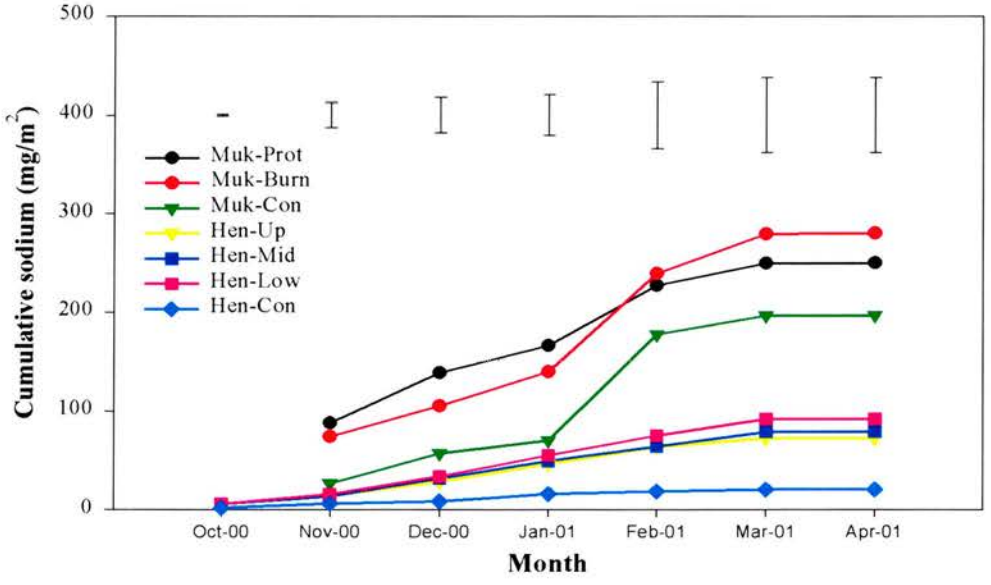


Figure 4.17. Cumulative sodium added in rainfall at Muk-Con and Hen-Con and throughfall (nutrients in rainfall + nutrients leached from the miombo woodland canopy) at Muk-Prot, Muk-Burn, Hen-Up, Hen-Mid and Hen-Low in the 2000/2001 rain season. Na had a similar trend to the previous season but with Muk-Burn having the highest cumulative Na at the end of the season (bars represent standard errors of the means, n = 7).

Throughfall measurements of NH_4^+-N at Mukuvisi Woodlands were significantly higher ($F_{6,\ 74} = 2.22$; $p<0.01$) in the woodland area burnt annually, Muk-Burn, than the protected woodland, Muk-Prot but were not significantly different from Muk-Con during the 1999/2000 rain season. Though burning was carried out in late July to early August, it is possible that it could have contributed nutrients through ash deposition on vegetation and was washed by the rain. Elsewhere aerosols from forest and/or grassland fires are known to be a potential source of nutrients in rainfall, throughfall and/or stem flow (Lewis, 1981; Jordan, 1982). The protected area and the control were not significantly different. During the 2000/2001 rain season Muk-Prot had significantly higher ($F_{6,\ 74} = 2.22$; $p<0.05$) NH_4^+-N than Muk-Burn. Similar trends were also observed for NO_3^--N for the same site. The results from the two seasons sampled were not similar. Other workers report significant differences in nutrients added in rainfall between seasons (Brasell and Gilmour, 1980).

Differences at the same sites from season to season could be due to a number of factors. Variation in insect damage due to herbivory (Parker, 1983), amount of rainfall (Brassel and Gilmour, 1980), the direction of the wind blowing industrial pollutants and seasonal differences in canopy cover and density are some of the possible explanations. A notable feature is the decrease in mineral N especially at Muk-Prot. This could be explained by a higher absorption of mineral N in rainwater by the more dense foliage or N fixation on leaf surfaces in the protected area (Carlisle *et al.*, 1967 and Eaton *et al.*, 1973; Proctor, 1987). At the Henderson Research Station, NH_4^+-N in throughfall at all the 3 woodland experiment sites was not significantly different ($p< 0.05$) from the control. The same trend was observed for nitrate-N in the woodland areas compared to the control. Ammonium-N and especially NO_3^--N sources are washed from the trees. At Henderson experiment areas the woodland canopy contributed insignificant mineral N. These results are in agreement with Edwards' (1982) findings that N is not easily leached from leaves. The results possibly confirm that most of the mineral N washed from the canopy at Mukuvisi was from industrial pollution. Canopy leaching therefore seems to contribute insignificant amounts of mineral N to the forest floor of miombo woodlands unaffected by industrial pollution unlike reports from other forest

Table 4.9. Input of nutrients (kg/ha/year) in rainfall at the Henderson Research Station and Mukuvisi Woodlands study sites and for selected sites in the tropics. Nutrient inputs in study areas were measured during the rainy season and were taken as inputs per year (over 12 months). The inputs in rainfall at the study sites are inputs at control plots (-nutrient not measured).

Location	Author	Rainfall (mm/yr)	Nutrient input (kg/ha/year)					
			Ca	Mg	Na	K	NH_4^+-N	NO_3^--N
Henderson (Zimbabwe)	This study (1999/2000)	1018	1.1	0.2	0.3	1.2	6.3	6.0
	This study (2000/2001)	856	0.9	0.2	0.2	1.2	2.9	2.8
Mukuvisi (Zimbabwe)	This study (1999/2000)	1181	16.1	1.6	6.8	7.8	6.9	7.8
	This study (2000/2001)	1169	7.0	0.8	2.0	7.8	4.3	3.1
Costa Rica	Hendry *et al.* (1984)	2820	1.4	1.0	5.8	2.5	1.15	0.5
Ghana	Nye (1961)	1850	12.7	11.3	-	17.5	11.5	2.5
Java	Bruijnzeel (1989)	4670	9.8	4.0	13.3	9.6	6.5	2.8
Puerto Rico	Jordan *et al.* (1972)	3750	21.8	4.9	57.2	18.2	-	-
Queensland	Westman (1978)	1650	3.2	5.9	50.0	3.4	-	<0.1
Queensland	Brasell & Gilmour (1980)	2520	2.3	2.9	20.8	4.5	-	-
Malaysia	Sinun *et al.* (1992)	3103	17.6	5.6	1.6	14.4	-	-

ecosystems (Nye, 1961; Eaton *et al.*, 1973; McColl and Bush, 1978; Brinson *et al.*, 1980). In the case of incident precipitation, the N source is the atmosphere. Lightning is also a potential source because it oxidizes nitrogen gas, it is however most likely that contributions from this source are low. In most of the publications, there is almost no mention of contributions to forest nutrient cycling from this source. In tropical ecosystems, rainfall occurs in the form of heavy storms that are normally accompanied by lightning. It is however difficult to measure how much this source contributes because some of the NOx fixed by lightning is transferred to the upper atmosphere (Franzblau and Popp, 1989; Liaw *et al.*, 1990).

Calcium additions at Mukuvisi ranged from 2750 mg/m^2 (Muk-Burn) to 1610 mg/m^2 (Muk-Con) in the 1999/2000 season (Figure 4.10 & 4.11). In the following rain season, calcium additions were lower ranging from 917 mg/m^2 (Muk-Burn) to 703 mg/m^2 (Muk-Con) possibly because of the short rain season. At Henderson calcium additions ranged from 586 mg/m^2 (Hen-Low) to 107 mg/m^2 (Hen-Con) and from 459 mg/m^2 (Hen-Low) to 93 mg/m^2 (Hen-Con) for the 1999/2000 and 2000/2001 rain seasons respectively (Figure 4.10 & 4.11). Magnesium additions were highest at Muk-Burn (545 mg/m^2) and lowest at Hen-Con (20 mg/m^2) in 1999/2000 rain season and a similar trend was observed in the 2000/2001 rain season (Figure 4.12 & 4.13). Potassium was the cation added in both rainfall and throughfall in highest concentrations. Amounts added ranged from 3600 mg/m^2 (Muk-Prot) to 119 mg/m^2 (Hen-Con) and from 1250 mg/m^2 (Muk-Burn) to 119 mg/m^2 (Hen-Con) for the 1999/2000 and 2000/2001 rain seasons respectively (Figure 4.14 & 4.15). Several workers have observed that K is one of the cations added in throughfall in high amounts (Eaton *et al.*, 1973; Bernhard-Reversat, 1975). Sodium additions, like the other cations, were higher in the 1999/2000 rain season compared to the relatively shorter 2000/2001 rain season (Figure 4.16 & 4.17). In the 1999/2000 season, additions ranged from 972 mg/m^2 (Muk-Prot) to 29 mg/m^2 (Hen-Con) whereas in the 2000/2001 season they ranged from 280 mg/m^2 (Muk-Burn) to 21 mg/m^2 (Hen-Con).

Cations in rainfall were very low at Henderson compared with Mukuvisi (Table 4.9), a result which is likely to be explained by the level of pollution in Harare. However the cations in rainfall at Henderson experiment areas were lower compared to measurements in other tropical forests (Table 4.9). Cations in throughfall were generally higher at Mukuvisi than Henderson woodland site (Figures 4.10-17). Additions of cations were much higher at Mukuvisi than at Henderson (Figures 4.10-17) probably because of industrial pollution (Jonnalagadda *et al.,* 1991). For all sites except Muk-Con, the amount of cations in rainfall and throughfall in descending order were K > Ca > Na > Mg. Potassium, therefore, was most easily leached cation from the miombo woodland canopy, whereas Mg was the least. During the 1999/2000 rain season, the order at Muk-Con was Ca > K > Na > Mg. Relative amounts of cations in rainfall and throughfall varies from place to place and also from season to season. Nyika *et al.,* (1996) found the order of cations in precipitation in an open area in Bulawayo, Zimbabwe, to be Ca > Na> K > Mg. Muk-Burnt had high nutrient contents, especially cations, possibly because of the ash and burnt tree stem surfaces that were washed by rain. The elevated concentration of nutrients, especially cations, during the first month of the rain season can be attributed to the effect of burning (Tables 4.5 & 4.6).

The amount of nutrients in incident rainfall changed as it passed through the miombo woodland canopy (Table 4.10). It was found that some NH_4^+ - N and NO_3^- - N was lost after the rain water passed through the canopy. However, there was a large increase in the quantities of nutrients Ca, Mg, K, and Na after the water passed through the canopy in the 1999/2000 rain season. During the 2000/2001 rain season less cations were removed from the canopy. The big difference between the two seasons could be explained by the longer 1999/2000 rain season. The long 1999/2000 rain season extended to June, the period when some leaves begin to senesce. It is likely that during this period cations are susceptible to leaching loss as observed by some workers (Gosz *et al.*, 1969; Eaton *et al.*, 1973). Additions of cations to miombo woodlands soils at Mukuvisi and Henderson experiment areas in throughfall forms an important input to

Table 4.10. Nutrients added ($mg/m^2/yr$) in throughfall from the canopy at Mukuvisi Woodlands and Henderson Research Station in the 1999/2000 and 2000/2001 rain season to the woodland floor. Negative sign indicates absorption and/or adsorption of the nutrient from rainwater by trees. A positive amount indicates leaching of nutrient from the canopy by rainfall. K and Ca were the most mobile cations.

SITE →	Muk-Prot		Muk-Burn		Hen-Up		Hen-Mid		Hen-Low	
SEASON →	99/00	00/01	99/00	00/01	99/00	00/01	99/00	00/01	99/00	00/01
NH_4^+ - N (mg/m^2)	-30	129	90	-25	-85	8	-68	31	-2	71
NO_3^- - N (mg/m^2)	-61	298	25	82	-31	2	-27	27	76	89
Ca (mg/m^2)	705	36	1140	214	351	339	361	323	480	366
Mg (mg/m^2)	326	90	386	117	98	28	125	32	118	36
K (mg/m^2)	2820	125	2560	473	511	421	608	404	620	434
Na (mg/m^2)	296	53	166	83	120	52	148	58	145	71

these ecosystems. Some of the cations transferred back to the soil can be easily re-used by vegetation because they are in an available form.

Chemical analyses of nutrients in rainfall and throughfall water samples were carried out on volume-weighted monthly composite samples. It would have been preferable to make analyses for each rainfall event in order to see the variability in nutrient contents. However, this was not possible because of constraints in logistics and resources.

Amounts of nutrients in throughfall were higher at Mukuvisi Woodlands which is in the city of Harare compared to Henderson Research Station, which is about 35 km north of Harare. Of all the experiment sites at Mukuvisi and Henderson, Hen-Con had the lowest nutrient contents. At Henderson there is likely to be less pollution compared to the study site in Harare. Mukuvisi Woodlands is located about 1 km from Msasa Industrial area where there is a fertilizer and a lime product manufacturing company. About 8 km northwest of Mukuvisi Woodlands, there is a cement factory which is well known for air pollution because of cement dust. This factory is also likely to contribute to cation additions at the Mukuvisi site, especially calcium. Jonnalagadda *et al.* (1991) found that Msasa industrial area was one of the areas in Harare with high air pollution. Unfortunately they only measured gaseous pollutants such as ammonia and sulphur dioxide.

Measurements at Muk-Con gave very high values that were comparable to those within the woodland. The open areas used as control were small and close to the wooded area. The minimum distance of control areas from the nearest canopy was about 5 m compared to a minimum of 20 m at Henderson Research Station. Within such short distances it is possible to have water from the wooded area being blown into the control rain gauges causing excessive contamination. A solution to this problem could have been the use of collectors raised above the canopy (Bruijnzeel, 1991). Jordan (1982) minimized this problem at control sites by having rainfall-collecting containers on poles 2 m above the ground in an open area approximately 100 m from the forest. At both sites Mukuvisi and Henderson this was not possible. The only option available at

Mukuvisi was locating the control rain gauges in the grassland area but rain gauges located there had to be removed within a few days because of animal disturbance.

Water collected in rain gauges within woodlands at both study sites was found to contain plant debris, frass (insect faeces and debris) and insects. The bulk of the plant and insect debris was prevented from falling into the water by the rain gauge funnel. It is possible that this could have elevated the nutrients measured in the water samples. At Mukuvisi Woodlands the same problem was encountered in control rain gauges where it was common to find ants and other insects in the water sample. At Henderson, this problem was less pronounced in the control rain gauges. The holes in the rain gauge funnel were coarse and in hindsight, filters with fine pores should have been used with the rain gauge funnels.

4.4.3. Nutrient additions in stem flow

Mean monthly nutrient concentrations in stem flow (Table 4.11 & 4.12) were found to be much higher than in throughfall (Table 4.5-8). This was expected (Eaton *et al.*, 1973; McColl and Bush, 1978 and Parker, 1983) because the nutrients contained in stem flow are derived from incident precipitation, the canopy and tree stem surfaces. Like throughfall, the concentrations of nutrients were higher at the beginning of the rain season because of high amounts of aerosols during this period (Lewis, 1981; Jordan, 1982). Though the concentration of nutrients in stem flow is higher compared to throughfall, the total amount of nutrients added to miombo woodland soils in stem flow is lower because the amount of water that moves through the forest as stem flow is very small (Tables 4:11-12 and Figures 4.17-22) (Jordan, 1978; Yawney *et al.*, 1978; Edwards, 1982).

Mineral ammonium-N and nitrate-N additions in 1999/2000 season were highest at Hen-Up (6.8 and 5.7 mg/m^2) followed by Hen-Low (6.8 and 5.4 mg/m^2) with the lowest in Hen-Mid (6.2 and 5.1 mg/m^2) (Figure 4.17-18). In the 2000/2001 season ammonium-N was highest in Hen-Mid (5.04 mg/m^2) and lowest in Hen-Up (4.36 mg/m^2). Nitrate-N was highest in Hen-Low (3.6 mg/m^2) and lowest in Hen-Up (3.4 mg/m^2). The total

Table 4.11. Mean monthly nutrient concentrations (mg/l) in stem flow water samples from Henderson experiment sites in the 1999/2000 rain season. (SE in parentheses).

Month	Nov. 1999	Dec. 1999	Jan. 2000	Feb. 2000	Mar. 2000	Apr. 2000	May. 2000	Jun. 2000
HEN-UP (n = 9)								
Stem-flow (ml/m^2)	25	266	649	840	637	256	480	42
pH	**6.48** (0.12)	**6.42** (0.10)	**6.25** (0.13)	**6.36** (0.10)	**6.10** (0.13)	**6.40** (0.10)	**6.05** (0.12)	**6.24** (0.09)
NH_4^+-N (mg/l)	**5.61** (1.65)	**2.81** (0.83)	**2.21** (0.26)	**2.16** (0.32)	**2.97** (0.32)	**1.57** (0.25)	**0.72** (0.18)	**0.89** (0.13)
NO_3^-N (mg/l)	**5.33** (0.73)	**1.44** (0.14)	**1.49** (0.15)	**2.96** (0.23)	**1.46** (0.12)	**1.20** (0.16)	**0.99** (0.10)	**0.73** 0.06)
Ca (mg/l)	**5.21** (0.82)	**2.10** (0.18)	**1.95** (0.35)	**1.97** (0.32)	**1.73** (0.35)	**1.56** (0.12)	**1.28** (0.26)	**1.33** (0.21)
Mg (mg/l)	**1.06** (0.25)	**0.68** (0.05)	**0.52** (0.09)	**0.38** (0.09)	**0.39** (0.11)	**0.45** (0.09)	**0.45** (0.12)	**0.35** (0.08)
K (mg/l)	**9.84** (1.84)	**5.28** (0.52)	**4.06** (0.35)	**4.04** (0.31)	**3.70** (0.61)	**2.85** (0.55)	**2.70** (0.44)	**2.18** (0.27)
Na (mg/l)	**3.25** (0.58)	**1.41** (0.37)	**1.95** (0.34)	**2.26** (0.40)	**1.11** (0.37)	**2.64** (0.39)	**1.27** (0.47)	**1.63** (0.24)
HEN-MID (n =11)								
Stem-flow (ml/m^2)	31	354	861	970	893	365	691	61
pH	**6.36** (0.14)	**6.31** (0.10)	**6.38** (0.09)	**6.29** (0.09)	**6.17** (0.11)	**6.38** (0.07)	**6.40** (0.09)	**6.36** (0.07)
NH_4^+-N (mg/l)	**7.99** (2.02)	**2.03** (0.24)	**1.88** (0.17)	**3.10** (0.36)	**1.27** (0.25)	**1.18** (0.23)	**0.96** (0.14)	**0.86** (0.08)
NO_3^-N (mg/l)	**4.97** (1.03)	**1.31** (0.11)	**1.46** (0.12)	**2.58** (0.31)	**1.37** (0.17)	**0.87** (0.14)	**0.86** (0.12)	**0.76** (0.08)
Ca (mg/l)	**3.28** (0.56)	**2.97** (0.42)	**2.26** (0.24)	**2.06** (0.17)	**1.67** (0.18)	**1.51** (0.27)	**1.19** (0.20)	**0.99** (0.19)
Mg (mg/l)	**1.10** (0.17)	**0.73** (0.06)	**0.57** (0.11)	**0.45** (0.10)	**0.50** (0.08)	**0.49** (0.08)	**0.37** (0.07)	**0.37** (0.06)
K (mg/l)	**9.68** (1.56)	**4.58** (0.54)	**3.60** (0.37)	**3.89** (0.63)	**4.14** (0.61)	**3.32** (0.32)	**2.67** (0.37)	**2.42** (0.34)
Na (mg/l)	**4.74** (0.72)	**2.44** (0.29)	**2.58** (0.19)	**1.99** (0.21)	**1.28** (0.36)	**2.20** (0.23)	**1.75** (0.19)	**1.45** (0.15)
HEN-LOW (n = 9)								
Stem-flow (ml/m^2)	29	295	801	913	835	287	606	37
pH	**6.46** (0.15)	**6.43** (0.08)	**6.73** (0.09)	**6.54** (0.09)	**6.36** (0.07)	**6.40** (0.08)	**6.25** (0.07)	**6.38** (0.10)
NH_4^+-N (mg/l)	**4.76** (1.71)	**1.99** (0.20)	**2.18** (0.37)	**3.49** (0.40)	**1.63** (0.25)	**1.05** (0.22)	**0.85** (0.13)	**1.01** (0.09)
NO_3^-N (mg/l)	**7.44** (2.50)	**1.44** (0.20)	**1.21** (0.17)	**2.89** (0.20)	**1.26** (0.09)	**0.90** (0.04)	**1.15** (0.10)	**1.20** (0.21)
Ca (mg/l)	**5.14** (1.15)	**3.13** (0.31)	**2.46** (0.23)	**1.77** (0.40)	**2.11** (0.34)	1.82 (0.27)	**1.42** (0.13)	**1.07** (0.23)
Mg (mg/l)	**0.96** (0.12)	**0.69** (0.08)	**0.63** (0.07)	**0.55** (0.15)	**0.56** (0.18)	**0.37** (0.08)	**0.37** (0.07)	**0.32** (0.07)
K (mg/l)	**12.80** (2.14)	**5.13** (0.75)	**5.34** (0.78)	**4.19** (0.38)	**5.29** (0.90)	**2.66** (0.42)	**2.77** (0.45)	**2.66** (0.47)
Na (mg/l)	**2.71** (0.57)	**2.17** (0.36)	**2.56** (0.42)	**1.71** (0.21)	**1.75** (0.37)	**1.80** (0.21)	**1.57** (0.28)	**1.65** (0.19)

Table 4.12. Mean monthly nutrient concentrations (mg/l) in stem flow water samples from Henderson experiment sites in the 2000/2001 season. (SE in parentheses).

Month	Oct. 2000	Nov. 2000	Dec. 2000	Jan. 2001	Feb. 2001	Mar. 2001
HEN-UP (n = 9)						
Stem-flow (ml/m^2)	88	692	433	541	740	576
pH	**6.65** (0.21)	**6.27** (0.14)	**6.20** (0.08)	**6.55** (0.17)	**6.30** (0.12)	**6.44** (0.06)
NH_4^+-N (mg/l)	**4.48** (0.97)	**0.95** (0.07)	**1.14** (0.18)	**2.03** (0.41)	**1.19** (0.19)	**1.46** (0.18)
NO_3^-N (mg/l)	**2.31** (0.30)	**1.03** (0.11)	**1.12** (0.09)	**1.16** (0.10)	**1.04** (0.17)	**0.97** (0.13)
Ca (mg/l)	**7.96** (1.32)	**3.10** (0.54)	**2.23** (0.23)	**1.23** (0.22)	**1.32** (0.18)	**1.23** (0.29)
Mg (mg/l)	**1.93** (0.36)	**0.49** (0.08)	**0.68** (0.05)	**0.46** (0.06)	**0.53** (0.11)	**0.37** (0.09)
K (mg/l)	**15.58** (4.75)	**4.95** (0.92)	**4.88** (0.21)	**5.10** (0.87)	**3.64** (0.43)	**2.43** (0.43)
Na (mg/l)	**3.89** (0.62)	**2.15** (0.52)	**2.39** (0.33)	**2.35** (0.52)	**2.00** (0.34)	**1.76** (0.33)
HEN-MID (n = 11)						
Stem-flow (ml/m^2)	197	957	621	708	1011	771
pH	**6.74** (0.26)	**6.14** (0.13)	**6.27** (0.10)	**6.65** (0.13)	**6.36** (0.10)	**6.48** (0.09)
NH_4^+-N (mg/l)	**6.52** (1.54)	**1.31** (0.19)	**1.12** (0.20)	**2.07** (0.33)	**1.66** (0.25)	**1.25** (0.17)
NO_3^-N (mg/l)	**2.58** (0.19)	**1.21** (0.06)	**1.03** (0.08)	**1.05** (0.10)	**1.13** (0.11)	**0.91** (0.12)
Ca (mg/l)	**7.07** (1.30)	**2.28** (0.35)	**2.58** (0.24)	**2.11** (0.63)	**1.65** (0.22)	**1.49** (0.26)
Mg (mg/l)	**2.04** (0.33)	**0.74** (0.10)	**0.74** (0.04)	**0.72** (0.14)	**0.67** (0.08)	**0.44** (0.06)
K (mg/l)	**16.14** (1.85)	**6.18** (1.44)	**4.98** (0.38)	**8.62** (1.82)	**3.70** (0.34)	**2.00** (0.29)
Na (mg/l)	**5.61** (0.67)	**2.11** (0.48)	**2.35** (0.33)	**3.26** (0.48)	**2.54** (0.28)	**1.67** (0.25)
HEN-LOW (n = 9)						
Stem-flow (ml/m^2)	165	777	535	616	847	663
pH	**6.94** (0.17)	**6.39** (0.17)	**6.34** (0.11)	**6.63** (0.08)	**6.36** (0.07)	**6.44** (0.08)
NH_4^+-N (mg/l)	**7.13** (1.91)	**1.43** (0.17)	**1.09** (0.10)	**1.55** (0.17)	**1.21** (0.17)	**0.95** (0.15)
NO_3^-N (mg/l)	**2.78** (0.17)	**1.24** (0.14)	**1.26** (0.09)	**1.14** (0.10)	**1.07** (0.11)	**0.97** (0.10)
Ca (mg/l)	**5.16** (0.81)	**2.93** (1.18)	**3.39** (1.01)	**2.56** (0.66)	**1.83** (0.24)	**1.83** (0.31)
Mg (mg/l)	**1.74** (0.14)	**0.84** (0.26)	**0.78** (0.07)	**0.74** (0.15)	**0.76** (0.15)	**0.45** (0.05)
K (mg/l)	**16.73** (1.71)	**15.17** (7.26)	**5.53** (0.42)	**13.08** (6.77)	**2.93** (0.37)	**2.09** (0.31)
Na (mg/l)	**5.12** (0.45)	**3.70** (1.52)	**2.76** (0.34)	**4.53** (1.63)	**2.19** (0.28)	**1.52** (0.15)

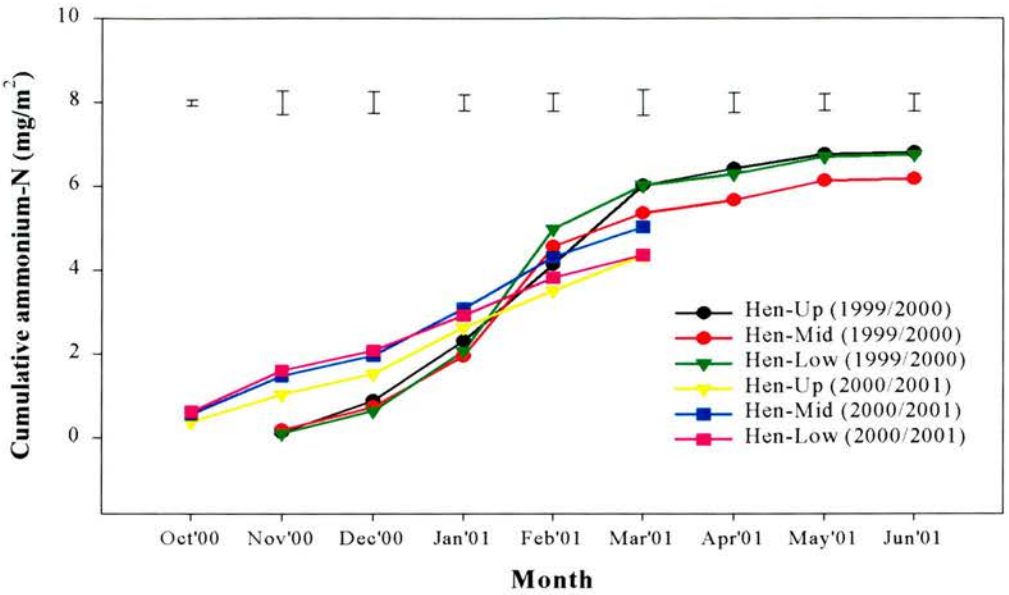


Figure 4.18. Cumulative ammonium-N added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of means, n = 3 for October 2000 and April to June 2001; n = 6 for November 2000 to March 2001).

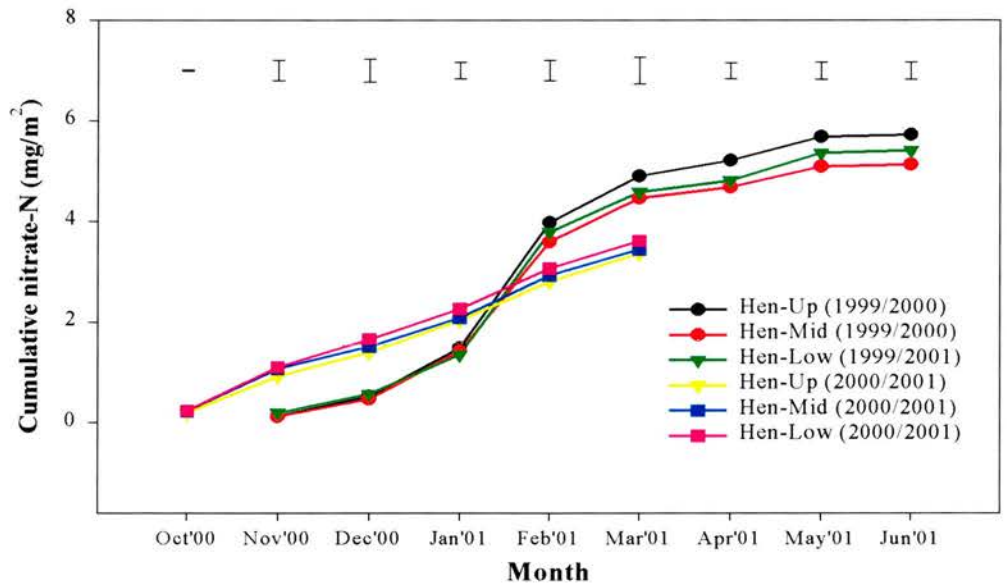


Figure 4.19. Cumulative nitrate-N added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of the means, n = 3 for October 2000 and April to June 2001 & n = 6 for November to March 2001).

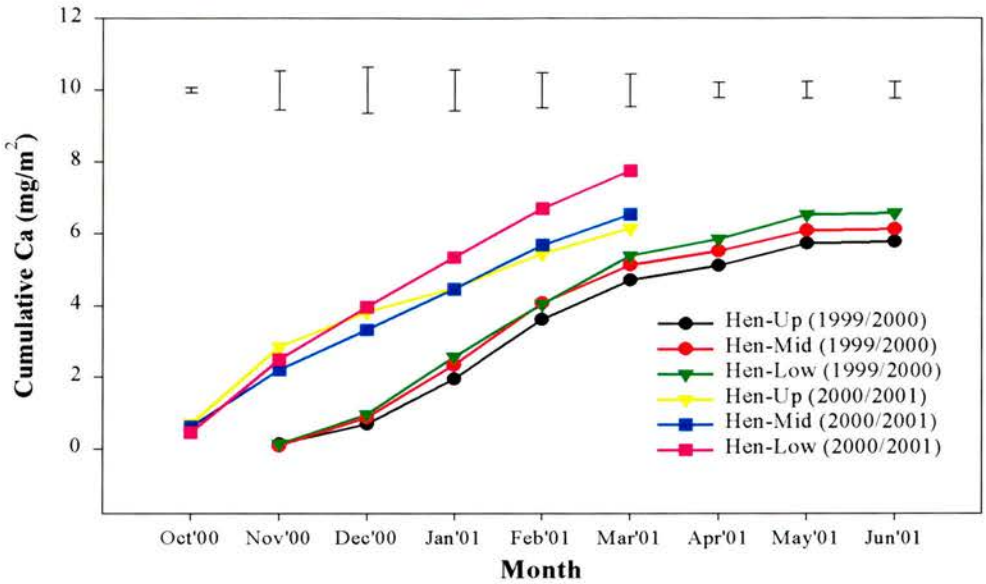


Figure 4.20. Cumulative calcium added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of means, n = 3 for October 2000 and April to June 2001 & n = 6 for November 2000 to March 2001).

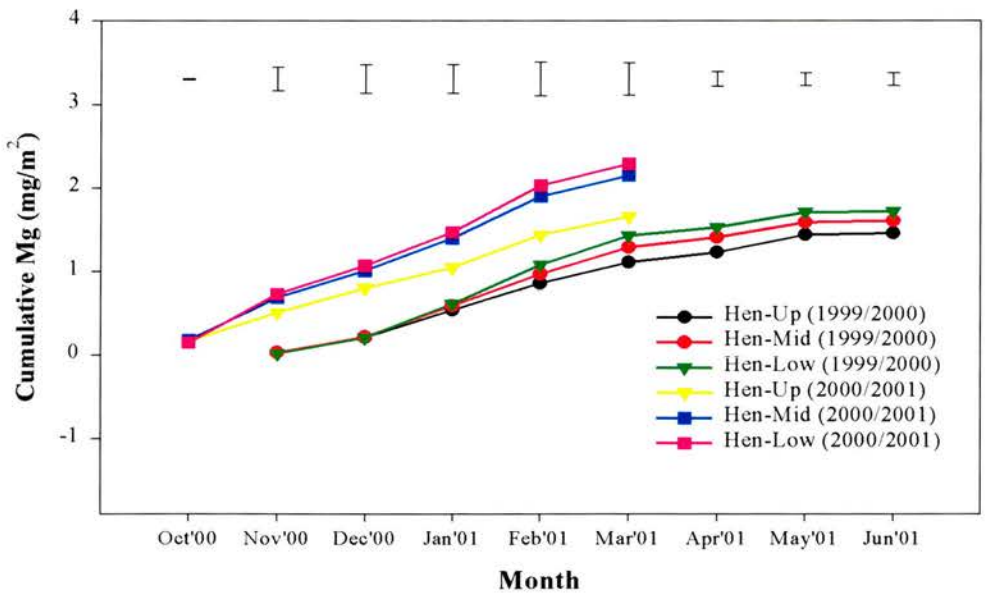


Figure 4.21. Cumulative magnesium added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of means, n = 3 for October 2000 and April to June 2001; n = 6 for November 2000 to March 2001).

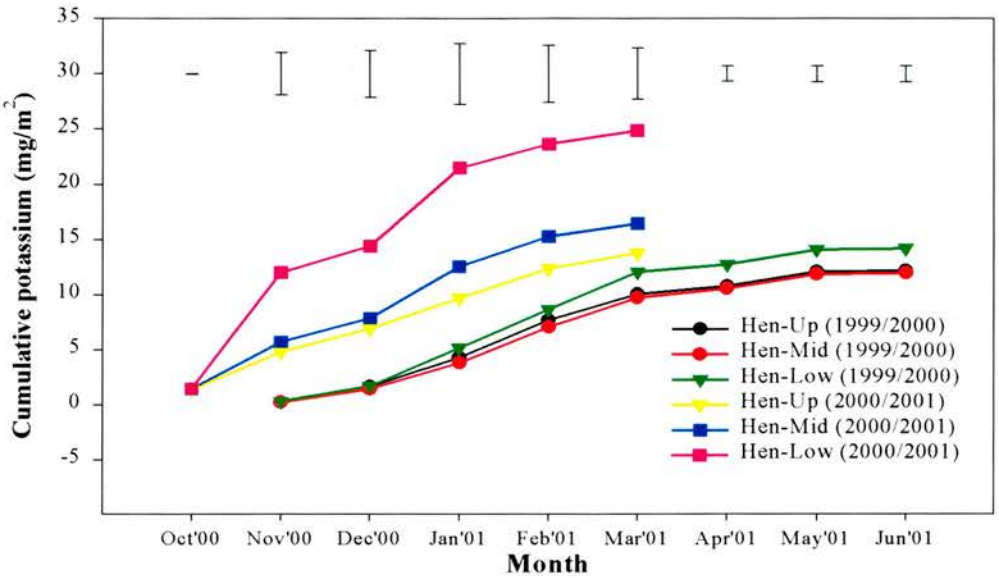


Figure 4.22. Cumulative potassium added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of means, n = 3 for October 2000 and April to June 2001 & n = 6 for November 2000 to March 2001).

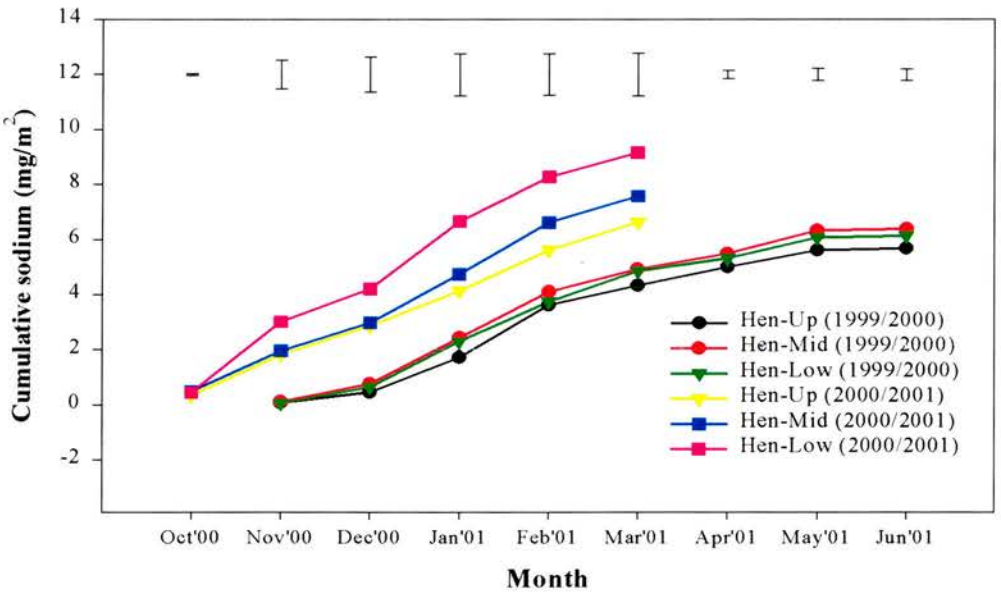


Figure 4.23. Cumulative sodium added to miombo woodland floors in stemflow at Hen-Up, Hen-Mid and Hen-Low experimental areas in the 1999/2000 and 2000/2001 rain seasons (bars represent standard errors of means, n = 3 for October 2000 and April to June 2001 & n = 6 for November 2000 to March 2001).

amount of mineral N added in stem flow was higher in the 1999/2000 rain season than in the 2000/2001 season.

The highest amount of calcium and magnesium was added at Hen-Low (6.6 and 1.7 mg/m^2 respectively) in the 1999/2000 rain season and the lowest was added at Hen-Up (5.8 and 1.5 mg/m^2 respectively) (Figure 4.19-20). Hen-Low also received the highest amount of potassium in stem flow (14.2 mg/m^2) and Hen-Mid had the lowest (11.9 mg/m^2) in the same season (Figure 4.21). However Hen-Mid received the highest amount of sodium (6.4 mg/m^2) and Hen-Up the lowest (5.7 mg/m^2) (Figure 4.22). The total amount of calcium, magnesium, potassium and sodium added to the woodland floor in stem flow in the 2000/2001 rain season was highest at Hen-Low and lowest at Hen-Up (Figure 4.18-22). More cations were added during the 2000/2001 rain season compared to the 1999/2000 season. Overall, the amount of cations added in stemflow were lower than those added in throughfall and many authors have reported similar results (Eaton *et al.*, 1973; Brinson *et al.*, 1980; Sinun *et al.*, 1992), highlighting the low contribution of nutrients in stem flow to the forest floor.

4.5. OVERVIEW

Rainfall was found to be an important input of nutrients especially mineral N. The quantities of nutrients in rainfall were altered as the rain water passed through the canopy. The amount of throughfall measured in woodlands was lower than the rainfall in open control areas because of canopy interception. Mineral N transferred or cycled in throughfall was very low possibly because of absorption and/or adsorption by the canopy. Rainfall at the same location added significant amounts of mineral N. Cations were lower in rainfall compared to mineral N, with Mg and Na being the lowest (<0.5 kg/ha/year). In throughfall cations were far higher than mineral N because of leaching from the canopy. K had the highest concentration of the cations leached from the canopy.

The proximity to urban industrial areas significantly influenced nutrient fluxes in rainfall. Both rainfall and throughfall contained significant amounts of nutrients at miombo woodlands in an urban area and should therefore be included in estimates of nutrient cycling in these environments. The concentration of nutrients in stemflow was higher than in throughfall. At the Henderson Research Station study site it was observed that termites covered tree trunks with soil. They removed and consumed some of the outer layer of the bark covered with soil. It is possible that the soil and bark material elevated nutrient concentrations in stemflow after being washed off by the rain. Compared to throughfall, nutrient additions in stemflow are lower because the amount of water moving along tree trunk surfaces is very low. In this study stemflow was found to be less than 1 % of annual rainfall.

Rainfall, throughfall and stem flow are not the only pathways by which nutrients are added and/or cycled in miombo woodlands. Other pathways like litter fall and decomposition of litter are also an important supply to vegetation. These will be discussed in the next chapter.

5. INTERNAL CYCLING OF NUTRIENTS IN MIOMBO WOODLANDS: *FOLIAR NUTRIENT UPTAKE, LITTER FALL AND LITTER DECOMPOSITION*

5.1. INTRODUCTION

Internal nutrient cycling involves the transfer and movement of nutrients within the woodland system, that is, soil, litter and vegetation. Some nutrients washed or leached from vegetation in through fall and stem flow are part of this within-woodland cycling. It was, however, found to be more appropriate to discuss them in the previous chapter together with nutrient additions in rainfall (chapter 4).

In chapter 4 inputs of nutrients to miombo woodlands were measured and additions in rainfall were found to be significant. This nutrient source is very important for the maintenance of miombo woodlands because miombo soils are generally of low fertility status, being acid, with low cation exchange capacity, low N, exchangeable bases and available P (Frost, 1996; Campbell *et al.*, 1996). Some of the nutrients in miombo soils are taken up by vegetation, an important nutrient sink. Some of the nutrients end up in tree leaves. Most of miombo woodland tree species are deciduous. Dry miombo woodlands (<1000 mm/annum) under which the study sites fall, shed a large proportion of their leaves from July to August and wet miombo woodlands (>1000 mm/annum) from August to September (Chidumayo and Frost, 1996). A small amount of litter is also shed during the year before the peak leaf fall period. Nutrients in shed leaves are therefore transferred to the woodland floor. On the soil surface litter undergoes decomposition, releasing nutrients in available form.

This study aims at measuring nutrient changes in dominant tree species leaves and quantifying the amount of litter fall and nutrients in litter in miombo woodlands. The chapter examines measurements of nutrients taken up in the leaves of the dominant tree species. The dominant tree species identified in Chapter 3, at Mukuvisi sites are *J. globiflora* and *B. spiciformis* and at Henderson Research Station *J. globiflora, B. spiciformis* and *B. boehmii*. Nutrient changes in foliar samples were therefore monitored

in these tree species from leaf development to senescence. The chapter also analyses nutrients transferred to the woodland floor in litter fall and nutrients released during decomposition using 7 mm mesh litter bags.

It is hypothesised that miombo woodlands are nutrient-limited and hence show an urgency to withdraw nutrients at senescence and for rapid decomposition of litter.

Objectives

The specific objectives of this study were:

i. to measure nutrients taken up in dominant miombo tree species and determine amounts withdrawn at senescence,
ii. to measure the amount of litter production and nutrients added in litter at the miombo study sites and
iii. to measure the amount of litter decomposed and the nutrients released over about a year

5.2. ASSESSMENT OF LITERATURE ON MIOMBO NUTRITION

Understanding nutrient cycling in miombo woodland ecosystems is important because soil nutrients, besides moisture, fire and herbivory, are a major ecological determinant of vegetation functioning, structure and composition in savanna ecosystems (Scholes and Walker, 1993; Campbell *et al.*, 1996; Frost, 1996). The major components of within-woodland nutrient cycling are uptake by vegetation, litter fall and litter decomposition.

5.2.1. Nutrient uptake in leaves by the dominant miombo tree species

Miombo woodland tree species produce new leaves or flush from the end of August to early October where leaf development occurs late. Leaf flush therefore occurs during the peak of the hot and dry season before the onset of the rain season in October/November (Chidumayo and Frost, 1996). Nutrients required for initial leaf development are re-translocated from other parts of the tree (Chapin, 1980). Uptake of soil nutrients from upper soil horizons, where a large proportion of nutrients are found,

mainly occurs after the onset of rain when the soil becomes moist in October to November.

Nutrient contents in trees can vary considerably during the period from leaf flush to senescence (Ernst, 1975; Chidumayo, 1994). Chidumayo (1994) reports a marked difference in N and P concentration in *J. globiflora* from 2.03 and 0.68 at leaf flush to 1.50 and 0.15 % dry weight at senescence respectively. Understanding patterns and changes in the nutrient contents of trees during the growing season is important in nutrient cycling studies. They can give an insight into adaptation and nutrient limitation of the ecosystem. Limiting nutrients are withdrawn from senescing leaves in relatively large amounts, an important adaptation to nutrient-poor systems. This is very important in miombo woodlands where the dominant tree species do not fix nitrogen. Changes in nutrient content are also important in food selection by animals and insects which depend on the woodland tree species (Jachmann, 1989).

Forest trees use various strategies to maintain and conserve nutrients. Most of the dominant miombo tree species are associated with ectomycorrhizae which are important in the uptake of nutrients, especially P (Högberg, 1981, 1982, 1986, 1992 and 1995 and Högberg & Piearce, 1986). Mycorrizhas are not only important in nutrient uptake but they are also important in the uptake of water by plants (Högberg, 1992). Most deciduous trees withdraw some nutrients from leaves thus reducing nutrients transferred to the woodland floor. It has been postulated that low nutrient loss is an adaptation of trees in nutrient-poor environments and in these environments, plants have features which lead to low nutrient loss such as nutrient withdrawal from leaves at senescence (Chapin, 1980; Vitousek, 1984; Aerts, 1990 & 1996). Re-absorption of nutrients is vital not only to the plants but also to most organisms that directly or indirectly depend on nutrients in plants (Killingbeck, 1996). Nutrients re-absorbed during senescence are most likely readily available for further plant growth, thus enabling plants to be less dependent on nutrients taken up from the soil. Ernst (1975) observed a decline in the amount of nutrients N, P and K in mature leaves of miombo tree species whereas Ca and Na increased until abscission. Similar observations have been reported with tree

species in semi arid savanna environments (Tolsma *et al.*, 1987). More data is required from different miombo woodlands sites to understand fully the nutrient cycling patterns and the influence of location.

5.2.2. Litterfall

Dry miombo woodland litterfall occurs continually in small amounts throughout the year, peaking in July and August. Timing of peak litterfall depends on moisture availability, occurring earlier in the dry season (May to October) when below average rainfall is received and with trees retaining leaves longer in years of above average rainfall (Frost, 1996).

Litterfall is a major component of nutrient cycling in forests. Measurements of litterfall and the amount of nutrients transferred to the forest and woodland floor are therefore critical in understanding nutrient dynamics. Measurement of nutrients in litter can give an insight into nutrients limiting production (Heaney and Proctor, 1989; Proctor, 1989) and indices of nutrient economy can be calculated using litter nutrient data (Vitousek, 1984; Scott, *et al.*, 1992). The patterns of nutrient cycling are diverse (Vitousek and Sanford, 1986), requiring many studies in dry tropical areas to ascertain general patterns. Studies of litterfall require at least twenty litter traps in a restricted random experimental design, evenly covering the study area, to get a reliable estimate of the mean (Proctor, 1983). A systematic experimental design can also be used where the main aim is establishing patterns and distribution of litterfall production. It is recommended that studies should be over at least 3 years and preferably 5 years. Proctor (1983) however points out that shorter periods of at least a year are acceptable where forests or woodlands such as miombo are almost completely deciduous.

Most of the litterfall studies have been carried out in temperate and moist tropical areas of the world (Edwards and Grubb, 1977; Likens *et al.*, 1977; Edwards, 1982; Brasell and Sinclair, 1983; Proctor *et al.*, 1983; Lowman, 1988; Heaney and Proctor, 1989; Scott *et al.*, 1992). More studies need to be carried out in seasonally dry tropical woodlands and forests especially in Africa. Miombo woodlands are important because

they occupy a very large area in central and southern Africa and are estimated to cover 2.7 million km^2, making it the most extensive vegetation formation on the African continent (Frost, 1996). However, in spite of the large area, litterfall data in miombo woodlands is sparse (Frost, 1996) as is information on dynamic processes generally.

5.2.3. Litter decomposition

Nutrients transferred from trees through litter fall maybe re-used by woodland vegetation after release through decomposition. Decomposing litter is therefore an important source of nutrients for plant growth in terrestrial ecosystems (Taylor *et al.*, 1989). The rate of nutrient release from decomposition determines primary production (Swift *et al.*, 1979). A study of litter fall should therefore be accompanied by decomposition studies so as to understand how fast nutrients in litter turn over to become available for re-use. Slow litter decay results in accumulation of nutrient stocks on the soil surface and therefore locks away nutrients needed by plants.

Litter decomposition is the physical and chemical breakdown of litter resulting in the release of nutrients in plant available form, some organic compounds and smaller litter particles. It involves leaching, comminution and catabolism (Swift *et al.*, 1979; Heal *et al.*, 1997). The decomposition process depends on:

a). environmental factors, like temperature and moisture,
b). the interaction of litter with the soil,
c). the nature of the decomposer community and
d) the chemical composition of the litter.

Environmental factors, temperature and moisture, influence the activity of the decomposer community (Swift *et al.*, 1979). Temperature affects rate of chemical reactions including enzyme-catalysed reactions which are characteristic of biological processes. Water is required by decomposer organisms for tissue growth and as a medium of activity. It indirectly affects other soil environment factors, such as, pH and aeration (Swift *et al.*, 1979). Water is also important in the leaching process. Other site

characteristics like species richness, soil pH and soil texture have been found to affect decomposition (Zimmer, 2002). Interaction of the litter with the soil is important because it makes litter more accessible to soil fauna. The decomposer community in savanna ecosystems, miombo woodlands included, is made up of micro-organisms, fungi, meso- and macro-fauna. Micro-organisms and fungi are involved in the catabolic breakdown process. Meso- and macro-fauna fragment litter into smaller particles and some ingest litter releasing simpler molecules in faeces. In savanna ecosystems, comminution is very important and is carried out mainly by termites and to a lesser extent beetles, millipedes and ants. There are termites throughout the savanna biome and they play an important role in nutrient cycling (Trapnell *et al.*, 1976, Jones, 1990; Lavelle *et al.*, 1994). Termites bring up finer soil material to the surface horizons, fragment, consume and move large quantities of litter into their nests where, in the case of fungus-cultivating species, it is broken down by fungus (Jones, 1990). Organic matter is conserved in termitaria. Overall, termites enrich the soil by concentrating carbon, N and exchangeable bases (Watson, 1976 & 1977) and the nutrients can be slowly released to the soil (Menaut *et al*, 1985). The nature of the material accumulated in termitaria varies with the nature of the soil environment.

The chemical composition of litter determines the rate of decomposition and nutrient release (Swift *et al.*, 1979; Melillo et al., 1982; Vitousek et al., 1994). Decomposition and nutrient release is positively correlated to concentrations of N and P and negatively correlated to C/N and C/P ratios (Aber and Melillo, 1980; Berg and Staaf, 1981; McClaugherty *et al.*, 1985; Taylor *et al.*, 1989; Mtambanengwe and Kirchmann, 1995). Decomposition rate and nutrient release is high for plant residues with high N contents (Swift *et al.*, 1979). Lignin content has also been observed to control decomposition when present in high concentrations (Berg and Staaf, 1981; Melillo *et al.*, 1982). Initial lignin to N ratios are reported to be highly correlated to the rate of decay (Blair, 1988). Polyphenols also affect decomposition and nutrient release (Vallis and Jones, 1973; Palm and Sanchez, 1991). Polyphenols negatively affect N release by forming stable polymers with many forms of compounds (Mueller-Harvey and McAllan, 1992).

Studies have shown that legume litter with high polyphenol concentrations immobilised N (Vallis and Jones, 1973; Palm and Sanchez, 1991).

A limited number of miombo litter decomposition studies have been carried out in Zimbabwe (Mtambanengwe and Kirchmann, 1995; Mafongoya and Nair, 1997; Nyathi, 1997; Musvoto *et al.*, 2000). Most of these studies looked at miombo litter as a potential soil amendment and thus focussed on litter decomposition as a source of nutrients for crops after incorporation into the soil. Incorporation of litter enhances the decomposition process and therefore decomposition is faster when litter is incorporated than when it is on the surface (Wilson *et al.*, 1986; Msumali *et al.*, 1993). In forest ecosystems, decomposition of litter occurs largely on the surface. Few studies of decomposition of litter on the forest floor have been carried out in relatively undisturbed miombo woodlands in Zimbabwe (Campbell *et al.*, 1988). Most surface decomposition studies of litter have been carried out in humid and sub-humid tropical conditions (Swift *et al.*, 1981). The present study looks at decomposition of litter on the soil surface and the associated nutrient release in miombo woodlands.

5.3. MATERIALS AND METHODS

5.3.1. Nutrient uptake in leaves by the dominant miombo tree species

Leaves from the dominant tree species, *J. globiflora* and *B. spiciformis* at Mukuvisi sites and *J. globiflora, B. spiciformis* and *B. boehmii* at Henderson Research Station sites were sampled from the lower to the middle of the canopy of each tree. Both Muk-Prot and Muk-Burn did not have *B. boehmii* trees. At Henderson, Hen-Up and Hen-Mid had *J. globiflora, B. spiciformis* and *B. boehmii* as the dominant tree species. Hen-Low did not have *J. globiflora* trees and *B. spiciformis* and *B. boehmii* were the dominant tree species present. The trees used in this study were randomly selected along the study transects and clearly labelled with plastic tags. Leaves were sampled at monthly intervals from leaf flush in the middle of September 1999 to July 2000 from the same trees.

The trees sampled were at least 2 m or more in height. It was found that smaller trees did not have sufficient leaves at leaf flush to allow for sampling the whole growing season. At Mukuvisi, 5 trees were selected along each transects in each experimental area at points about 40 m apart. The first sampling point was 40 m from the boundary fence between Muk-Prot and Muk-Burn areas. A total of 60 trees were sampled, 30 for each tree species (Table 5.1). At Henderson, in each experimental area, 3 trees were sampled along 2 of the transects and 4 trees from the third transect for each dominant tree species. Trees selected were about 40 m apart with the middle tree selected at the middle of each transect. The fourth tree sampled along the third transect was sampled from one randomly selected position of the 3 sampling points identified. A total of 80 trees were therefore sampled at Henderson.

At both study sites, sometimes tree species were not found exactly at the identified sampling points but in such cases the tree nearest to the point was selected. Sampling included trees ranging in size from 2 m in height. Different tree size categories for each tree species were sampled so as to have a representative sample. Nyathi and Campbell (1994) however, did not find any significant differences in nutrient foliar nutrient content among different age (height) classes of *B. spiciformis* miombo trees. Samples were immediately taken to the laboratory, oven dried at 60 ^{o}C for about 48 hours and weighed. The oven dry samples were milled before analyzing for N, P, K, Ca, Mg and Na using the methods described in section 3.2.2.

5.3.2. Litterfall

Fine litter fall (< 2 cm) was measured from the beginning of September 2000 to the end of August 2001 using litter baskets made from hessian material (plastic sack material with very fine pores) which can hold litter but allow rainwater to drip out. The baskets had a diameter of 1 m and a height of 0.5 m. The basket frames and its 4 legs were made of thick (5 mm) galvanized iron wire rods. In the field the legs were firmly pushed into the soil allowing the basket to stand 0.5 m above the ground (Plate 5.1).

Table 5.1. Number of trees and tree species sampled at experimental sites at Mukuvisi Woodlands and Henderson Research Station.

EXPERIMENT AREA	Tree Species	Transect	No. of trees sampled
MUK-PROT	B. spiciformis	1	5
		2	5
		3	5
	J. globiflora	1	5
		2	5
		3	5
MUK-BURN	B. spiciformis	1	5
		2	5
		3	5
	J. globiflora	1	5
		2	5
		3	5
HEN-UP	B. spiciformis	1	3
		2	4
		3	3
	J. globiflora	1	4
		2	3
		3	3
	B. boehmii	1	3
		2	4
		3	3
HEN-MID	B. spiciformis	1	4
		2	3
		3	3
	J. globiflora	1	3
		2	3
		3	4
	B. boehmii	1	4
		2	3
		3	3
HEN-LOW	B. spiciformis	1	3
		2	3
		3	4
	B. boehmii	1	4
		2	3
		3	3

Plate 5.1 Litter basket (1.0 m diameter, 0.5 m height and ≈0.5 above ground) used for collecting litter fall at Mukuvisi Woodlands and Henderson Research Station experimental sites.

At Mukuvisi Woodland sites, a total of 30 baskets were employed, 15 in Muk-Prot and 15 in Muk-Burn. The baskets were located randomly at restricted regular areas (Proctor, 1983) about 40 m apart along transects starting from the point 40 m from the boundary fence between Muk-Prot and Muk-Burn. At Henderson sites, 3 baskets were located along each transect in each experiment area in the same way as at Mukuvisi. The baskets were located in restricted regular areas of about 40 m apart with the middle basket approximately in the centre of each transect in each experiment area. Each experimental area therefore had a total of 9 baskets. Though it is recommended that a minimum of twenty litter traps are used in litterfall studies (Proctor, 1983), it was not possible during this research, especially at Henderson sites, because of logistics problems.

Litter was collected weekly from each basket during the rain season (November to April) to avoid leaching of nutrients by rain. In the dry season, litter was collected fortnightly. Litter from each basket was mixed and weighed at the end of each month. Litter from each basket was carefully separated every month into leaflets, rachids, twigs and bark (< 2 cm), flowers, fruits (pods + seeds) and trash. The litter fraction trash was made up of litter, like insect debris, which could not be placed into other groups. After separation, litter fractions were weighed, after oven drying at 60 ^{o}C. Composite samples of litter fractions for all litter baskets in each transect in each experimental area were used for chemical analysis. Thus, each experimental area had 3 samples for each litter fraction, when present, each month. Nutrients N, P, K, Ca, Mg and Na were analysed in the litter fraction from composite samples after milling using methods outlined in section 2.2.3.

5.3.3. Litter decomposition

At Mukuvisi, 2 decomposition sites along each transect in each woodland experiment area were identified. The sites were located randomly near the litter baskets along each transect, making a total of 6 decomposition sites in each experiment area. At Henderson, 2 decomposition sites were also randomly identified close to litter baskets, making a total of 6 decomposition sites in each experimental area.

Litter bag experiments are used to determine decomposition rates and nutrient release under field conditions (Anderson and Ingram, 1993; Zech and Kögel-Knabner, 1994). Standard litter bags recommended by the Tropical Soil Biology and Fertility Program (TSBF) (0.33m x 0.33m) made from polyvinyl with 7 mm mesh were used in this experiment (Anderson and Ingram, 1993). Litter used in the study was collected over 12 months using 6 litter baskets from September 1999 to August, 2000 at Mukuvisi Woodlands (Muk-Prot & Muk-Burn). The average litter fall was used to calculate the amount of litter to use in litter decomposition bags. As a result of these preliminary tests 33 g of litter (dry weight), equivalent to 3.3 tonnes/ha was used. The litter was carefully placed inside litter bags so that there was no compression of the enclosed litter and to allow free access to most groups of macro-fauna. At each decomposition site, 9 litterbags were randomly placed on the ground at the end of September, 2000. Litter bags were then placed on the woodland floor surface so as to represent litter that falls from trees. The litter bags were clearly labelled with aluminium tags. Litter was characterized before decomposition by analysing total lignin, polyphenols, cellulose, hemicellulose, C, N, P, K, Ca, Mg and Na.

A litter bag was randomly selected from each decomposition site in November, January, March, May and July. Samples were gently washed to remove any soil attached to the litter bag and the litter inside ensuring that no sample was lost. Samples were then oven dried at 60 ^{o}C for 48 hours, milled and analysed for total lignin, polyphenols, cellulose, hemicellulose, C, N, P, K, Ca, Mg and Na using methods outlined in section 2.2.3.

At two Muk-Burn decomposition sites, 3 and 4 litter bags were found to be missing. At Henderson Research sites, there was an intense fire during the first week of October, which destroyed most of the litterbags. Litterbags with fresh litter were therefore used to replace all litterbags at both Henderson and Mukuvisi experiment sites. A set of 5 litterbags was therefore used at each decomposition site because only a limited number of litter bags were available.

5.3.4. Data Analysis

Nutrient uptake and litter fall data were analysed using one way analysis of variance. Decomposition and nutrient release data were analysed using kinetic functions.

5.4. RESULTS AND DISCUSSION

5.4.1. Nutrient uptake in leaves by the dominant miombo tree species

Nutrient concentrations in leaves were found to vary during the growing season, that is, from leaf development to senescence. For all the three dominant miombo tree species, *J. globiflora, B. spiciformis* and *B. boehmii*, N, P and K increased from the beginning of leaf flush to a maximum and then declined as the leaves senesced (Fig. 5.1, 2 & 3). Thus young leaves have more N, P and K compared to mature and senescing leaves. Ca and Na increased as the leaves matured in all the 3 tree species. Mg content increased slightly during the growing season and then decreased to almost the initial level. Changes in Mg in *J. globiflora and B. spiciformis* followed the same trend. Ernst (1975) observed a decline in the concentrations of nutrients N, P and K in mature leaves of miombo tree species and an increase in Ca and Na until abscission. Similar results have been observed elsewhere with deciduous tree species in semi arid savanna environments (Tolsma *et al.*, 1987). It is believed that withdrawal of nutrients as leaves senesce is an adaptation by plants in nutrient poor conditions (Chapin, 1980; Vitousek, 1984; Aerts, 1996).

Reliable estimates of withdrawal or re-absorption efficiency need to correct for possible changes in specific leaf mass or leaf area. The commonly used reliable estimates of nutrient re-absorption are total nutrient pools in the entire canopy and the total amount of nutrients per leaf or per unit leaf area (Aerts, 1996). Nutrients re-absorbed or seasonal nutrient changes were calculated by subtracting the nutrient concentration at senescence from the concentration when leaves were mature in November and expressed as a percentage (Tables 5.2, 5.3 & 5.4). Expressing nutrient re-absorption this way was found to be adequate because mature miombo tree leaves do not change significantly in leaf area (Ernst, 1975). Ernst, (1975) reports a leaf area of 54.8 ± 6.5 cm^2, 130.3 ± 12.4 cm^2 and 58.8 ± 7.9 cm^2 for mature leaves of *B. boehmii*, *B.*

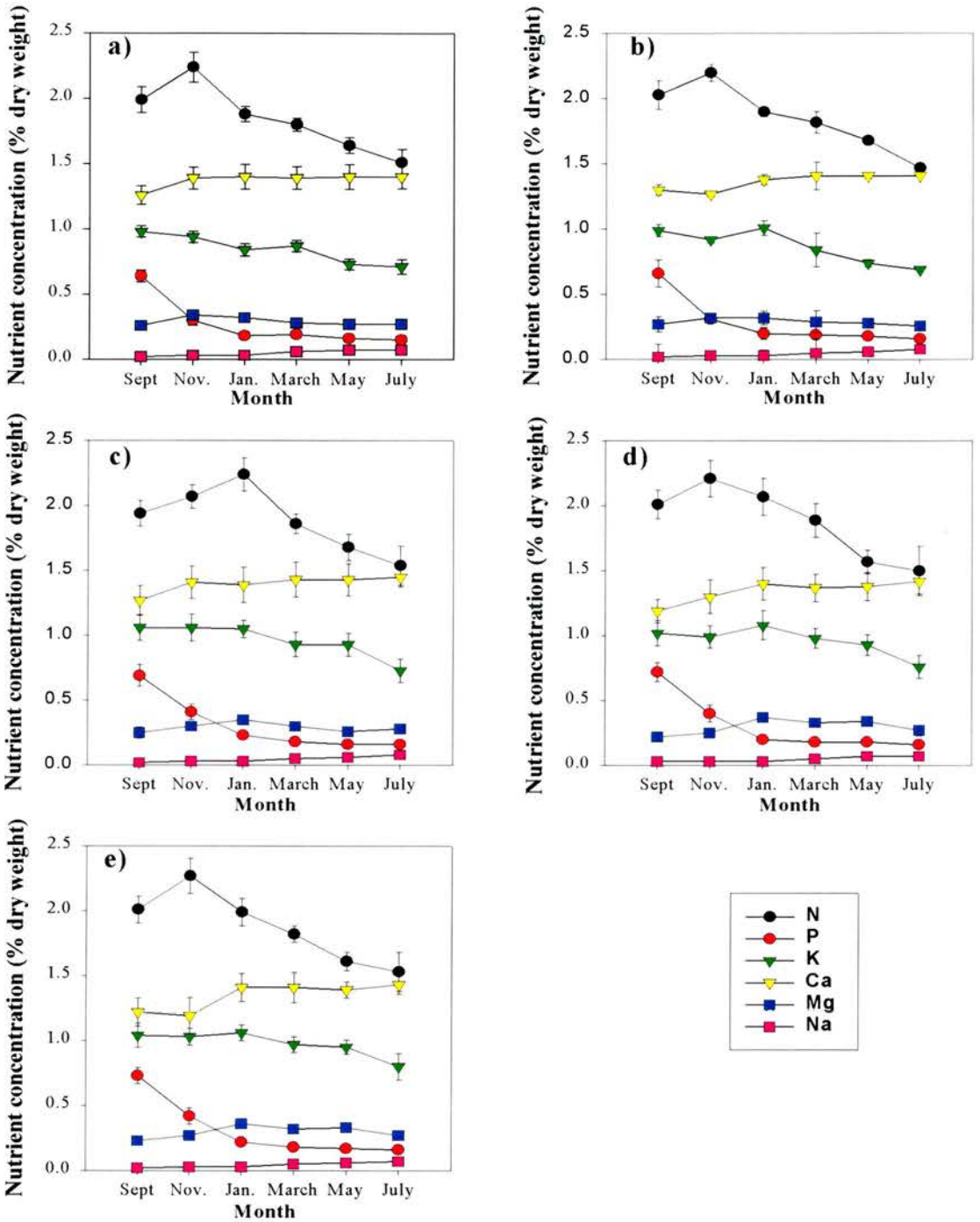


Figure 5.1: Nutrient variation in leaves of *B. spiciformis* from leaf development to senescence at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and Hen-Low experimental sites. Leaves were sampled from leaf flush in September 1999 to the beginning of senescence in July 2000 (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 10).

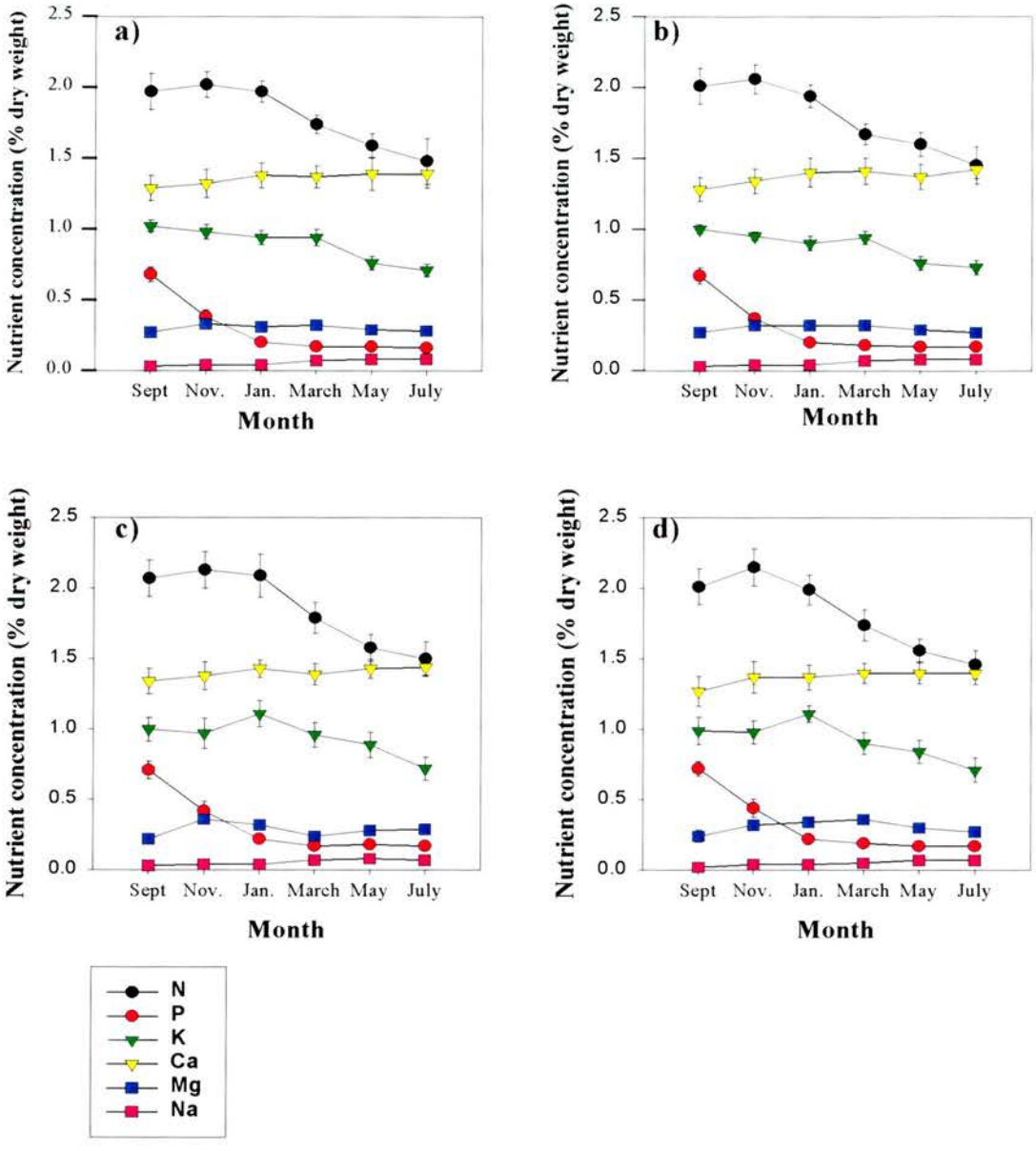


Figure 5.2. Nutrient concentration in leaves of *J. globiflora* from leaf development to senescence at a) Muk-Prot, b) Muk-Burn, c) Hen-Up and d) Hen-Mid experiment sites. Experimental site Hen-low did not have *J. globiflora* trees. Leaves were sampled from leaf flush in September 1999 to the beginning of senescence in July 2000 (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 10).

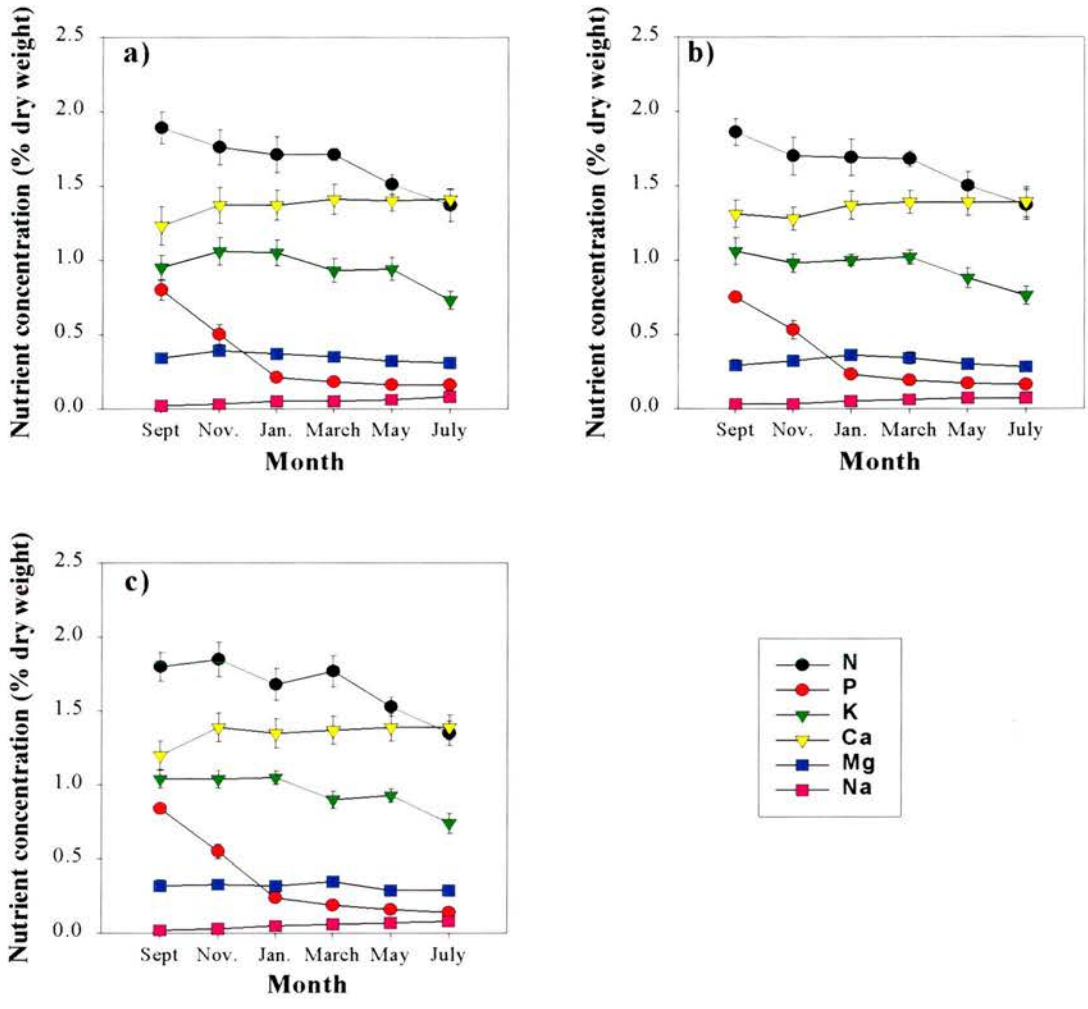


Figure 5.3. Nutrient concentration in leaves of *B. boehmii* from leaf development to senescence at a) Hen-Up, b) Hen-Mid and c) Hen-Low experimental sites. *B. boehmii* trees were only at Henderson Research Station sites. Leaves were sampled from leaf flush in September 1999 to the beginning of senescence in July 2000 (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 10)

spiciformis and *J. globiflora* respectively. For all species 22 to 33 %, 48 to 75 %, 22 to 31 % of leaf N, P and K were reabsorbed respectively. Results showed that a greater percentage of P was re-absorbed, possibly indicating that P is the most limiting nutrient at the study sites. Results of N re-absorption obtained in this study are similar to those found by Ernst (1975). Ernst (1975) reports that re-absorption of N in dominant miombo woodland tree species *J. globiflora, B. spiciformis* and *B. boehmii* ranged from 26 to 40 %. Aerts (1996) reports that about half of N and P in tree leaves maybe re-absorbed during senescence.

Chidumayo (1994) observed a higher P re-absorption of 80 % compared to 60 % for N in Zambian miombo tree species. N and P are believed to be the most limiting nutrients in savanna and tropical forests (Vitousek, 1984; Tolsma *et al.*, 1987; Högberg, 1992) and hence the need by trees to conserve these nutrients. K was also withdrawn from senescing leaves. K sources in soils are weathering soil minerals and decaying plant litter and animal remains. As soon as K is released from these sources it can be easily lost through leaching. This could possibly explain why miombo and other forest trees reabsorb K. The Ca and Na content in leaves increased by 0 to 20 % and 75 to 167 % respectively. Mg decreased by between 12 to 21 % in *J. globiflora and B. boehmii* leaves. In *B. spiciformis* leaves, results indicate that no Mg was re-absorbed at Hen-Mid and Hen-Low. Overall the trends of changes in nutrient concentration in the leaves of the dominant miombo woodland tree species were found to be similar.

In miombo woodlands where leaf flush occurs during the dry season, uptake of soil nutrients especially in the topsoil, where a large percentage of nutrients are found, is difficult because of the very low moisture contents. A nutrient reserve within the plant, which is easily accessible for plant growth is therefore important.

Differences in nutrient contents in leaves of miombo trees at Henderson and Mukuvisi sites were small. Generally Henderson sites had higher nutrient levels, however this difference was not statistically significant. It was expected that Henderson trees would have higher nutrient contents because the soils are heavier with higher clay content, CEC

Table 5.2. Seasonal changes of nutrient concentration in *B. spiciformis* at Mukuvisi and Henderson experimental sites. Mature leaves (%) is nutrient concentration in leaves in November and senescent leaves (%) is nutrient concentration in leaves in July. (s.d. – standard deviation)

Nutrient	Experiment Site	Mature leaves (%nutrient ± s.d.)	Senescent leaves (%nutrient ± s.d.)	Seasonal change (%)
N	Muk-Prot	2.24 ± 0.44	1.51 ± 0.40	-32.6
	Muk-Burn	2.20 ± 0.25	1.47 ± 0.01	-33.2
	Hen-Up	2.07 ± 0.28	1.54 ± 0.47	-25.6
	Hen-Mid	2.21 ± 0.45	1.50 ± 0.60	-32.1
	Hen-Low	2.27 ± 0.43	1.53 ± 0.47	-32.6
P	Muk-Prot	0.30 ± 0.15	0.15 ± 0.05	-50.0
	Muk-Burn	0.31 ± 0.10	0.16 ± 0.01	-48.4
	Hen-Up	0.41 ± 0.19	0.16 ± 0.10	-61.0
	Hen-Mid	0.40 ± 0.20	0.16 ± 0.06	-60.0
	Hen-Low	0.42 ± 0.19	0.16 ± 0.05	-61.9
K	Muk-Prot	0.94 ± 0.17	0.71 ± 0.22	-24.5
	Muk-Burn	0.92 ± 0.08	0.69 ± 0.01	-25.0
	Hen-Up	1.06 ± 0.33	0.73 ± 0.28	-31.1
	Hen-Mid	0.99 ± 0.27	0.76 ± 0.28	-23.2
	Hen-Low	1.03 ± 0.21	0.80 ± 0.32	-22.3
Ca	Muk-Prot	1.39 ± 0.17	1.40 ± 0.36	+0.7
	Muk-Burn	1.27 ± 0.08	1.41 ± 0.02	+11.0
	Hen-Up	1.41 ± 0.39	1.45 ± 0.24	+2.8
	Hen-Mid	1.30 ± 0.41	1.42 ± 0.30	+9.2
	Hen-Low	1.19 ± 0.44	1.43 ± 0.24	+20.2
Mg	Muk-Prot	0.34 ± 0.09	0.27 ± 0.10	-20.6
	Muk-Burn	0.32 ± 0.10	0.26 ± 0.02	-18.8
	Hen-Up	0.30 ± 0.12	0.28 ± 0.09	-6.7
	Hen-Mid	0.25 ± 0.12	0.27 ± 0.13	+4.0
	Hen-Low	0.27 ± 0.11	0.27 ± 0.11	0
Na	Muk-Prot	0.03 ± 0.01	0.07 ± 0.03	+133.3
	Muk-Burn	0.03 ± 0.02	0.08 ± 0.02	+166.7
	Hen-Up	0.03 ± 0.02	0.08 ± 0.02	+166.7
	Hen-Mid	0.03 ± 0.01	0.07 ± 0.02	+133.3
	Hen-Low	0.03 ± 0.02	0.07 ± 0.02	+133.3

Table 5.3. Seasonal changes of nutrient concentration in *J. globiflora* at Mukuvisi and Henderson experimental sites. The Hen-Low experimental site did not have *J. globiflora* tree species. Mature leaves (%) is nutrient concentration in leaves in November and senescent leaves (%) is nutrient concentration in leaves in July. (s.d. – standard deviation)

Nutrient	Experiment Site	Mature leaves (%nutrient ± s.d.)	Senescent leaves (%nutrient ± s.d.)	Seasonal change (%)
N	Muk-Prot	2.02 ± 0.36	1.48 ± 0.62	-26.7
	Muk-Burn	2.06 ± 0.40	1.45 ± 0.51	-29.6
	Hen-Up	2.13 ± 0.41	1.50 ± 0.39	-29.6
	Hen-Mid	2.15 ± 0.41	1.46 ± 0.32	-32.1
P	Muk-Prot	0.38 ± 0.18	0.16 ± 0.07	-57.9
	Muk-Burn	0.37 ± 0.09	0.17 ± 0.06	-54.1
	Hen-Up	0.42 ± 0.21	0.17 ± 0.07	-59.5
	Hen-Mid	0.44 ± 0.20	0.17 ± 0.07	-61.4
K	Muk-Prot	0.98 ± 0.20	0.71 ± 0.17	-27.6
	Muk-Burn	0.95 ± 0.12	0.73 ± 0.19	-23.2
	Hen-Up	0.97 ± 0.34	0.72 ± 0.26	-25.8
	Hen-Mid	0.98 ± 0.25	0.71 ± 0.27	-27.6
Ca	Muk-Prot	1.32 ± 0.38	1.39 ± 0.39	+5.3
	Muk-Burn	1.34 ± 0.34	1.42 ± 0.25	+6.0
	Hen-Up	1.38 ± 0.32	1.44 ± 0.18	+4.3
	Hen-Mid	1.37 ± 0.36	1.40 ± 0.25	+2.2
Mg	Muk-Prot	0.33 ± 0.08	0.28 ± 0.08	-15.2
	Muk-Burn	0.32 ± 0.11	0.27 ± 0.09	-15.6
	Hen-Up	0.36 ± 0.12	0.29 ± 0.12	-19.4
	Hen-Mid	0.32 ± 0.11	0.27 ± 0.09	-15.6
Na	Muk-Prot	0.04 ± 0.01	0.08 ± 0.02	+100.0
	Muk-Burn	0.04 ± 0.02	0.08 ± 0.02	+100.0
	Hen-Up	0.04 ± 0.01	0.07 ± 0.03	+75.0
	Hen-Mid	0.04 ± 0.02	0.07 ± 0.01	+75.0

Table 5.4. Seasonal changes of nutrient concentration in *B. boehmii* at Henderson experimental sites. Mukuvisi experimental sites did not have *B. boehmii* tree species. Mature leaves (%) is nutrient concentration in leaves in November and senescent leaves (%) is nutrient concentration in leaves in July. (s.d. – standard deviation)

Nutrient	Experiment Site	Mature leaves (%nutrient ± s.d.)	Senescent leaves (%nutrient ± s.d.)	Seasonal change (%)
N	Hen-Up	1.76 ± 0.38	1.37 ± 0.34	-22.2
	Hen-Mid	1.70 ± 0.40	1.32 ± 0.32	-22.4
	Hen-Low	1.85 ± 0.37	1.35 ± 0.25	-27.0
P	Hen-Up	0.50 ± 0.21	0.16 ± 0.06	-68.0
	Hen-Mid	0.53 ± 0.20	0.16 ± 0.05	-69.8
	Hen-Low	0.55 ± 0.16	0.14 ± 0.04	-74.5
K	Hen-Up	1.06 ± 0.29	0.73 ± 0.20	-31.1
	Hen-Mid	0.98 ± 0.19	0.76 ± 0.19	-22.4
	Hen-Low	1.04 ± 0.19	0.74 ± 0.21	-28.8
Ca	Hen-Up	1.37 ± 0.39	1.41 ± 0.22	+2.9
	Hen-Mid	1.28 ± 0.24	1.39 ± 0.32	+8.6
	Hen-Low	1.39 ± 0.31	1.39 ± 0.26	+0.0
Mg	Hen-Up	0.39 ± 0.08	0.31 ± 0.08	-20.5
	Hen-Mid	0.32 ± 0.10	0.28 ± 0.09	-12.5
	Hen-Low	0.33 ± 0.07	0.29 ± 0.06	-12.1
Na	Hen-Up	0.03 ± 0.02	0.08 ± 0.02	+166.7
	Hen-Mid	0.03 ± 0.02	0.07 ± 0.02	+133.3
	Hen-Low	0.03 ± 0.02	0.08 ± 0.02	+166.7

and exchangeable bases (Appendix 3). Soils at Mukuvisi sites are sandy and shallow with a depth range of 40 to 50 cm onto soft weathering granite. Granite derived soils are generally sandy and of lower fertility status than soils derived from mafic parent material such as at the Henderson sites.

5.4.2. Litterfall

The total amount of miombo woodland litter measured every month increased gradually from October 2000 to a maximum in July and August 2001 (Fig. 5.4). Most of the litter fell during the dry season from May to August (September), the time when there is water stress. In tropical areas litterfall is highest during the dry season, because of the need to conserve water (Gray, 1983; Proctor *et al.*, 1983; King and Campbell, 1994; Mtambanengwe, 2000). Litterfall measured ranged from 2.20 to 4.44 t/ha/year (Table 5.5). Some work carried out in miombo woodlands has reported a litterfall range of 2.61 to 4.26 tons/ha/year with leaves contributing a large proportion of this amount (Malaisse *et al.*, 1975; Frost, 1996). This is comparable to results obtained in this study. Muk-Prot had the highest amount of litter for most of the period under study. Total litterfall measured was in the order of Muk-Prot >Muk-Burn >Hen-Low>Hen-Up>Hen-Mid (Table 5.5). Henderson experimental sites were expected to have more litterfall because they are on relatively more fertile and clayey soil compared to Mukuvisi sites. Henderson sites were used for grazing cattle up to about 1997 and it is highly likely that some trees were removed some years back to increase grass production. Sites on similar soils like Hen-Mid and Hen-Low would normally have a higher tree density (pers. observation) because of slope position and drainage. Muk-Prot however had the highest tree density in the present study (Chapter 3), hence the higher litterfall. The most abundant tree species at this site is *J. globiflora*. From field observations, *J. globiflora* trees appeared to produce far more leaves compared to *B. spiciformis* of the same height, though measurements were not made to compare leaf production. It is possible that this could also have contributed to the higher litterfall. The same reason could be used to explain litterfall at Muk-Burn, which was second highest after Muk-Prot.

Table 5.5. Total amount of litter and nutrients transferred to the woodland floor at Mukuvisi and Henderson experimental sites from September 2000 to August 2001. (SE – Standard Error of the means)

Experiment site	Total amount of litter ($g/m^2/yr$)	Total amount of nutrient added in litter ($g/m^2/year$)					
		N	P	K	Ca	Mg	Na
Muk-Prot	444.4	6.52	1.02	2.67	5.38	0.86	0.21
Muk-Burn	300.6	4.36	0.70	1.86	3.68	0.59	0.14
Hen-Up	237.2	4.00	0.61	1.60	2.97	0.53	0.13
Hen-Mid	220.5	3.66	0.55	1.53	2.87	0.49	0.12
Hen-Low	244.8	4.24	0.64	1.69	3.13	0.56	0.13
SE	41.0	0.51	0.08	0.21	0.46	0.07	0.02

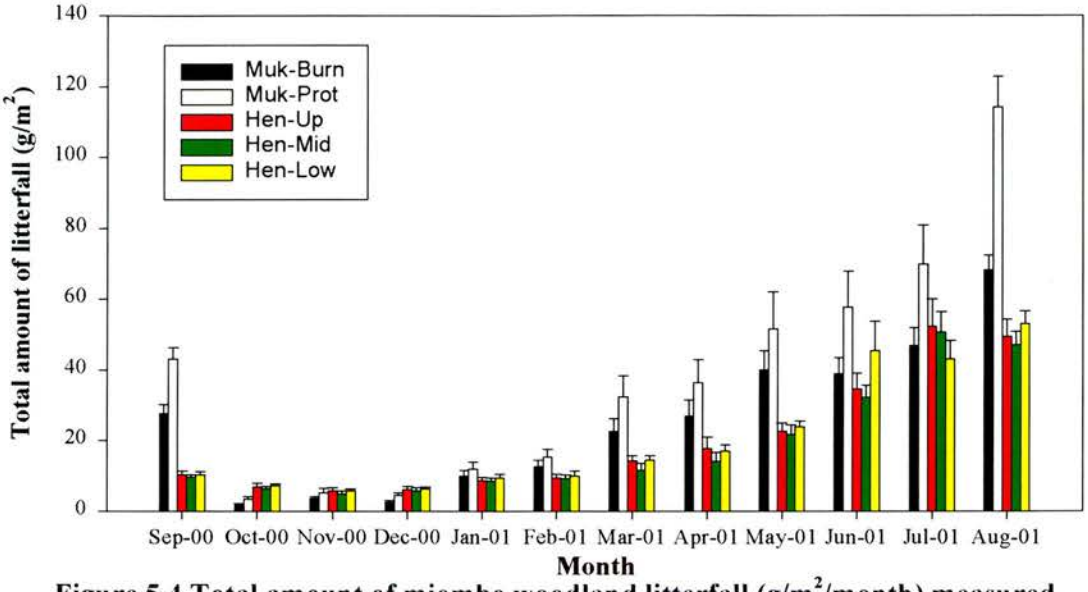


Figure 5.4 Total amount of miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites n = 9).

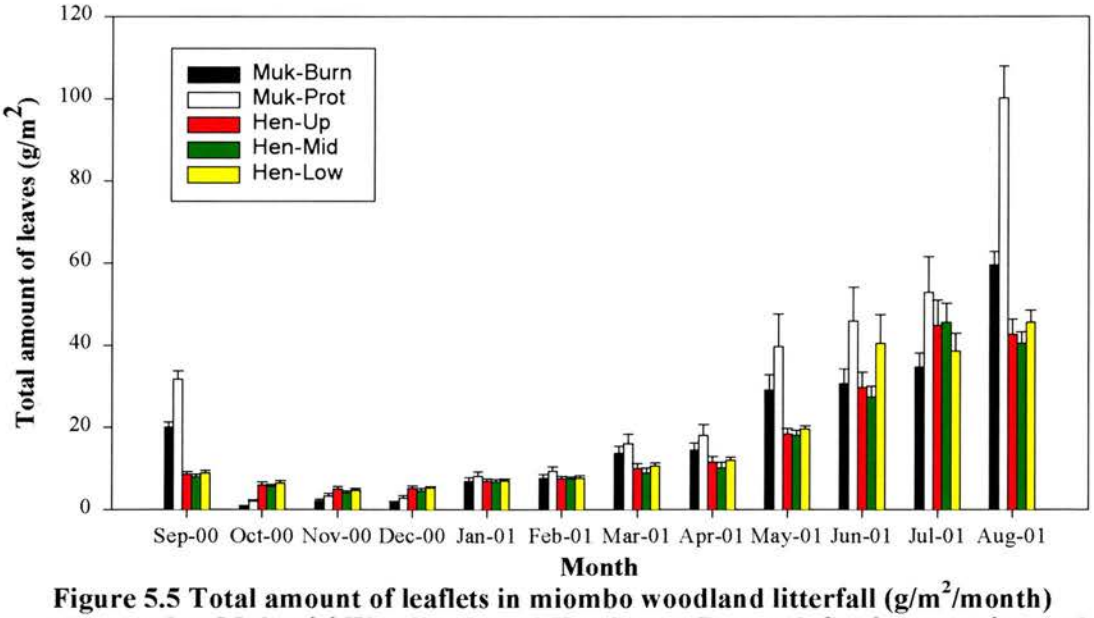


Figure 5.5 Total amount of leaflets in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

The amount of litterfall is important in estimating nutrient turnover but amounts can vary from year to year depending on climatic conditions especially rainfall. Mtambanengwe (2000) found that litterfall at a miombo woodland site ranged from 2.83 to 5.08 t/ha/year over a five-year period.

The monthly total amount of leaflets and rachids in miombo litter showed a similar pattern to that of the total monthly litter (Fig. 5.5 & 5.6). The leaflets were the dominant litter fraction in miombo litter making up more than 90 % of the litter. The amount of rachids was far much lower than leaflets although rachids are part of the whole leaf. Mtambanengwe (2000) made similar observations in a miombo woodland on granite derived sandy soils. It is possible that some rachids are not shed but become permanently part of the small branches after shedding leaflets. The amounts of twigs and bark were slightly higher in September 2000 and from March to August 2001 (Fig. 5.7). During these months, the amount of twigs and bark showed a similar pattern.

Flower litter was highest during the period January to May 2001 declining from June to August (Fig. 5.8). During the other months no flowers were observed in miombo litter. The time when flowers are found in litter depends on flowering patterns of miombo tree species. Most miombo woodland trees and shrubs have been observed to flower immediately after leaf flush, during the warm and dry season, from September to October, before the rains and *B. spiciformis* flower from August to October (Chidumayo and Frost, 1996). *Julbernardia* species are an exception with *J. globiflora* flowering from November to April (Campbell *et al.*, 1988). From the results it is likely that most of the flower litter during the period January to May was from *J. globiflora* trees. During the period June to August flower litter is from several tree species, *B. spiciformis* included.

The amount of pods and seeds were combined and plotted as fruits (Fig. 5.9). Pods were found in litter throughout the year with the highest amounts in September 2000 and the period June to August 2001.

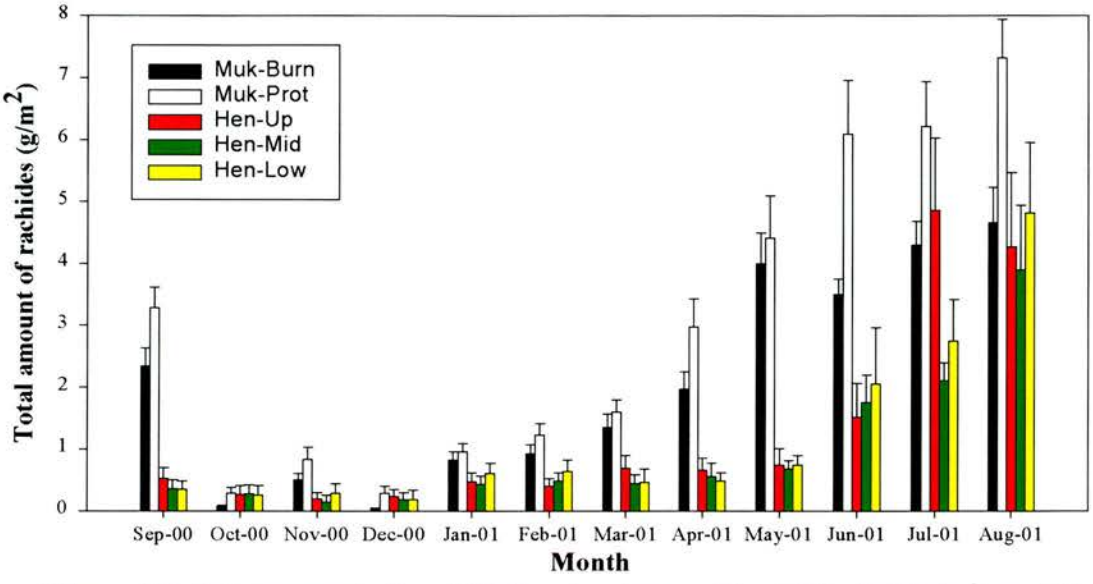


Figure 5.6. Total amount of rachids in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

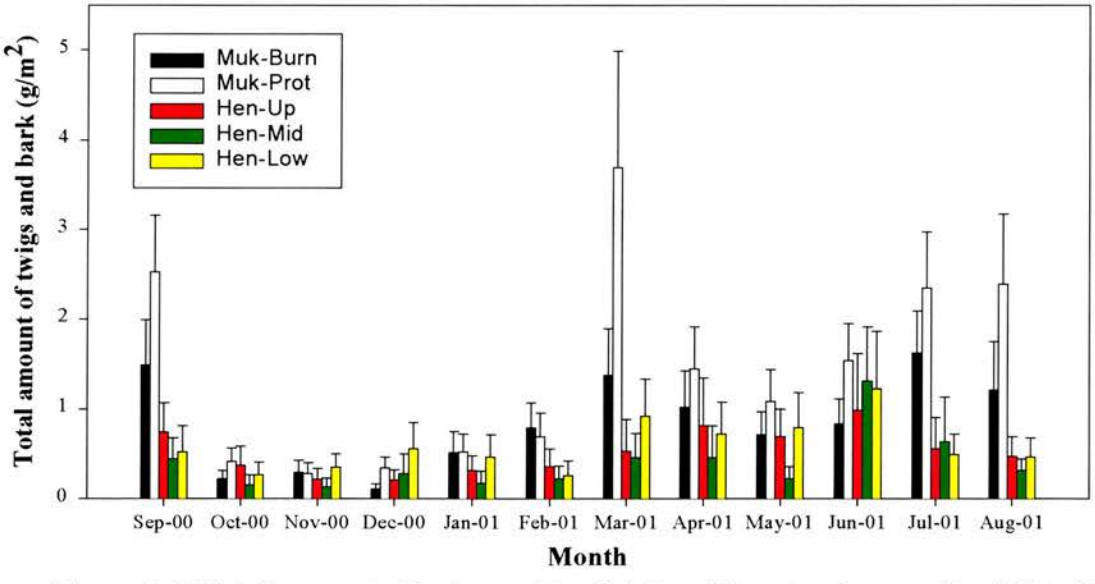


Figure 5.7. Total amount of twigs and bark (<2 cm) in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

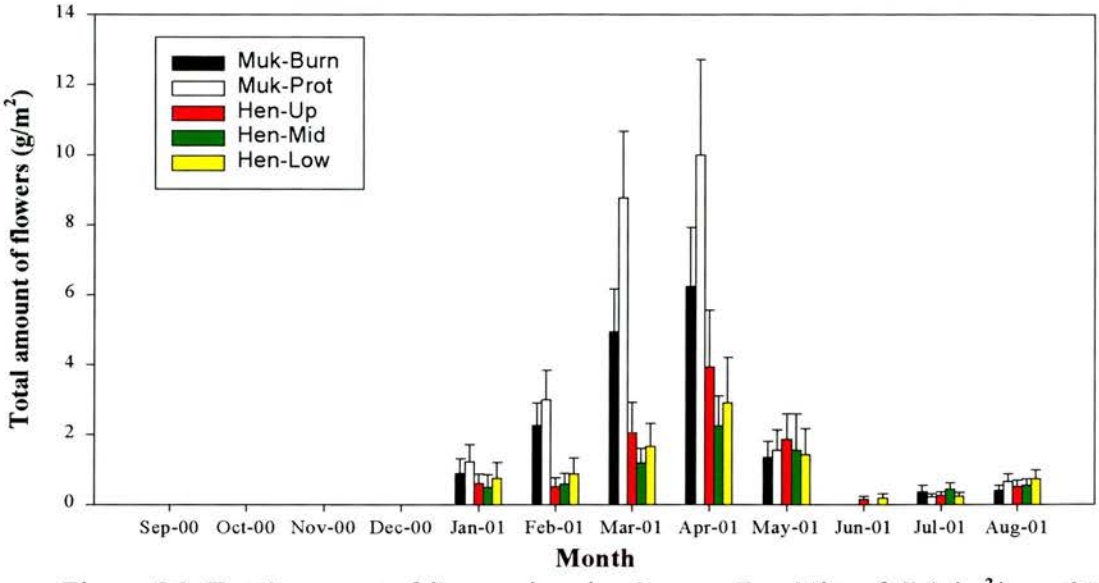


Figure 5.8. Total amount of flowers in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

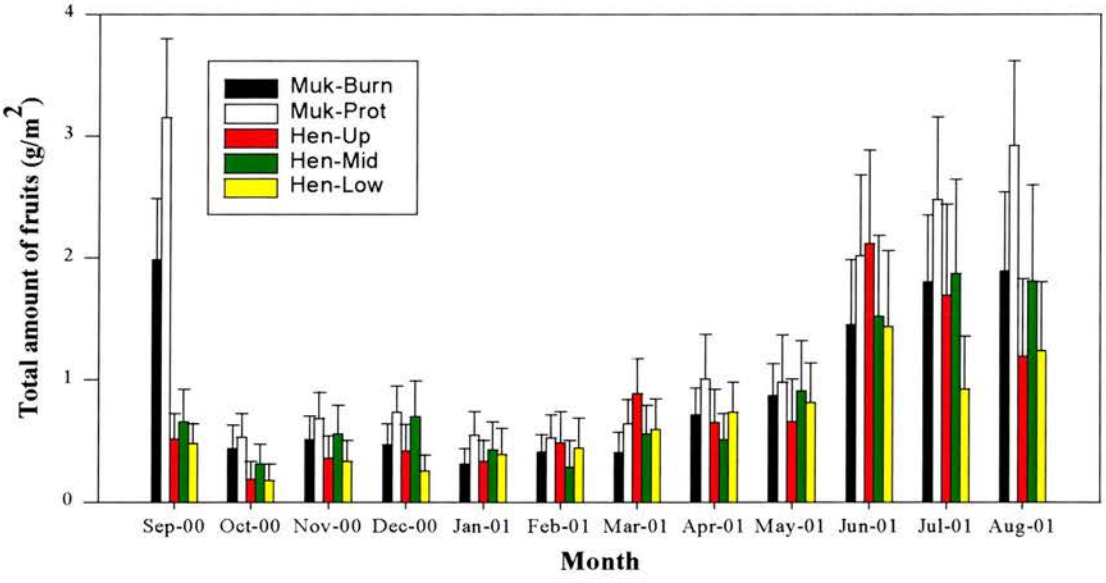


Figure 5.9. Total amount of fruits (pods + seeds) in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

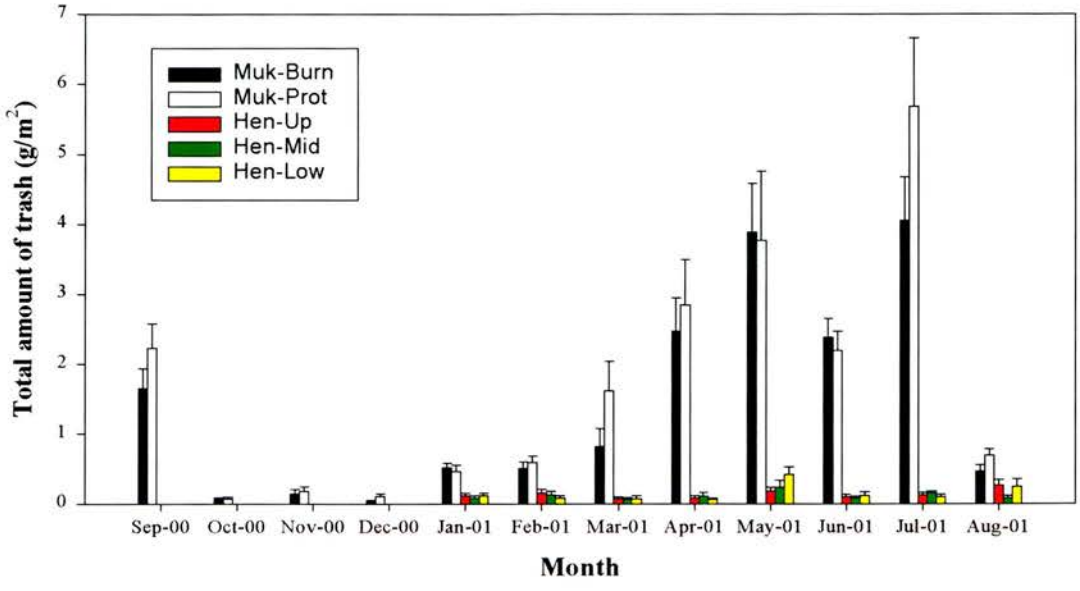


Figure 5.10. Total amount of trash in miombo woodland litterfall (g/m^2/month) measured at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of the means, Mukuvisi sites, n = 15 and Henderson sites, n = 9).

It was observed that some of the pods remain on the tree for a long time and in some cases to the next season before being shed. This could explain the continuous presence of pods in litter. Some pods are not immediately shed when they explode to disperse seed. Though pods were found throughout the year, seeds were only found in September 2000 and May to August 2001. These results possibly indicate that pods shed during the other period do not have seeds, have failed to dehisce to release seed or they released seeds already but took longer to shed. Fruit production in miombo woodlands varies from year to year (Chidumayo and Frost, 1996). At other miombo sites, workers observed that fruit and seed dispersal occurred mainly in the late dry season from August to November (Strang, 1966; Ernst, 1988; Chidumayo and Frost, 1996). There is a possibility that some trees do not produce fruit every year (Strang, 1966; Malaisse, 1978; Ernst, 1988).

Trash in litter was higher at the Mukuvisi sites compared to Henderson sites (Fig.5.11). It was suspected that handling of litter samples might have contributed to the high amount of trash. Rough handling can crush some litter resulting in higher amounts of trash. However, it is possible that there was a higher amount of insect debris and insect leaf and plant damage at Mukuvisi sites resulting in higher quantities.

The amounts of nutrients in litter fractions are presented as cumulative nutrients in Figures 5.12 to 5.17 and total annual amounts in Table 5.4. Most of the nutrients transferred to the woodland floor in litter are in the leaves. Though the amount of flowers shed was low and over fewer months, they contributed more nutrients compared to the other litter fractions. The nutrients N, K, Ca, Mg and Na in litter increased sharply in March and April (Figure 5.12 to 5.17) corresponding to a steep increase in litter fall (Figure 5.4) at all the experiment sites. An increase in litter fall therefore resulted in higher amounts of nutrients being transferred to the woodland floor. P increased uniformly from November to the end of the litter fall period in August. P occurred in small amounts in foliar samples. It had the highest withdrawal resulting in very low amounts in litter.

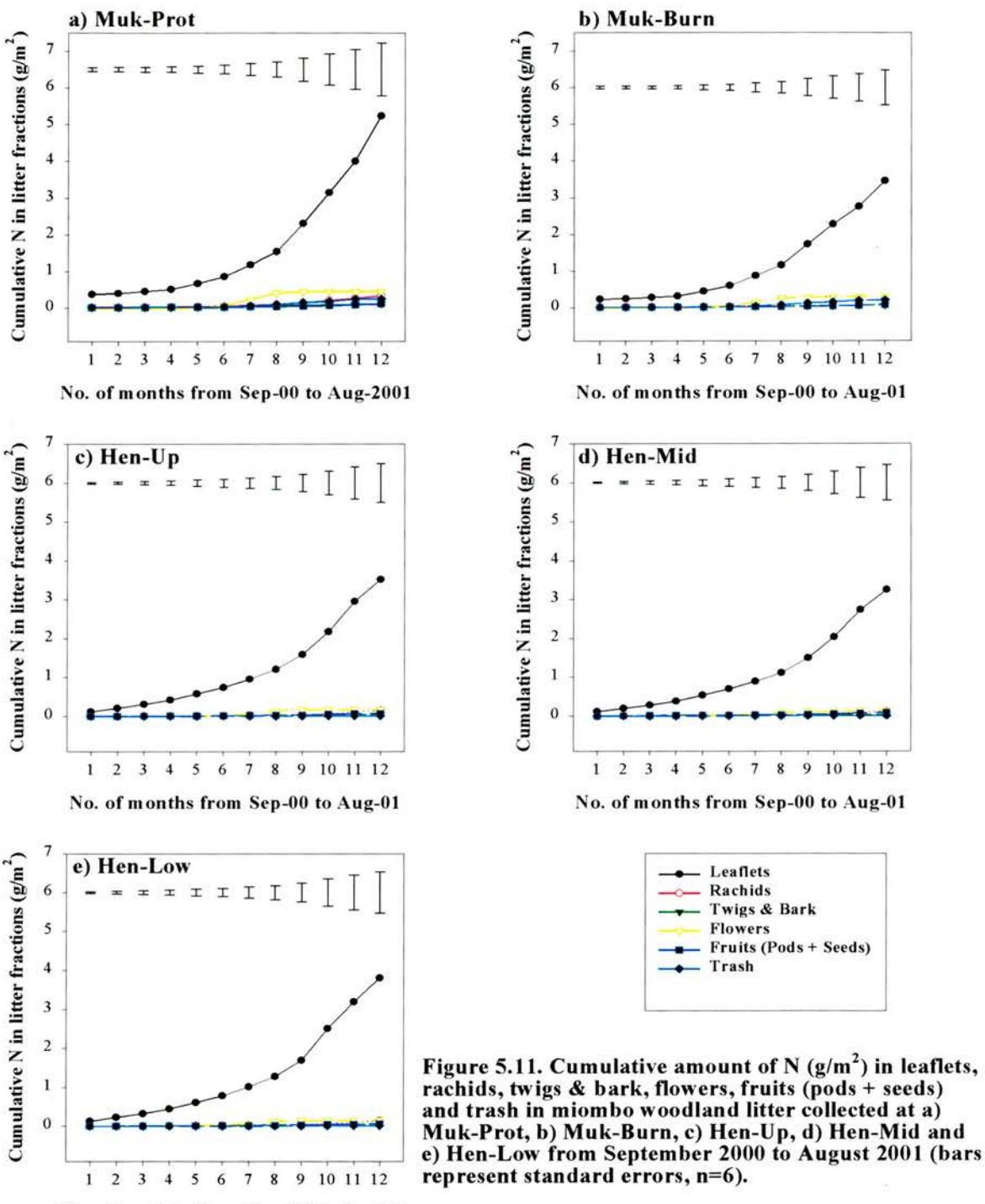


Figure 5.11. Cumulative amount of N (g/m^2) in leaflets, rachids, twigs & bark, flowers, fruits (pods + seeds) and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

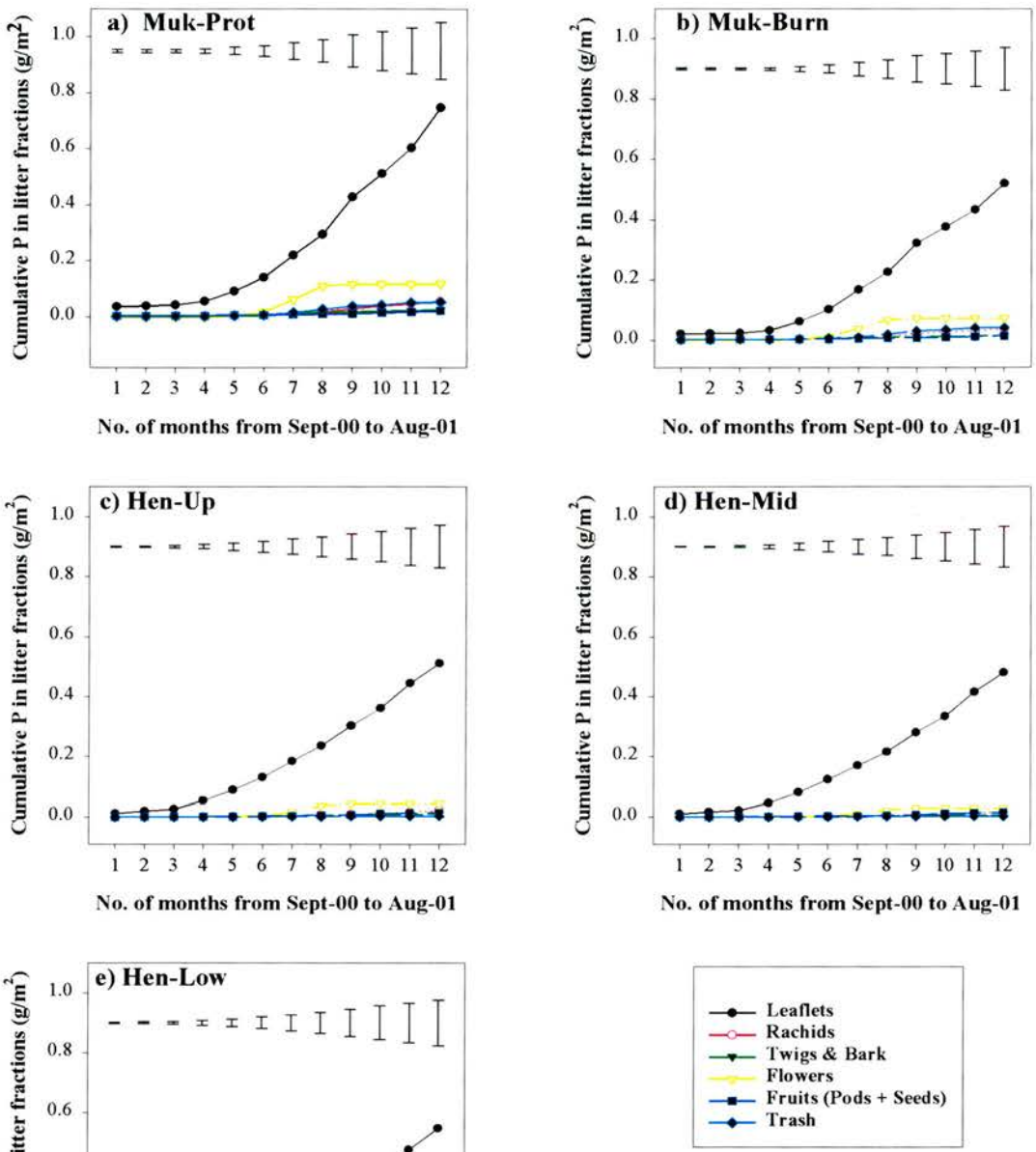


Figure 5.12. Cumulative amount of P (g/m^2) in leaflets, rachids, twigs & bark, flowers, pods, seeds and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

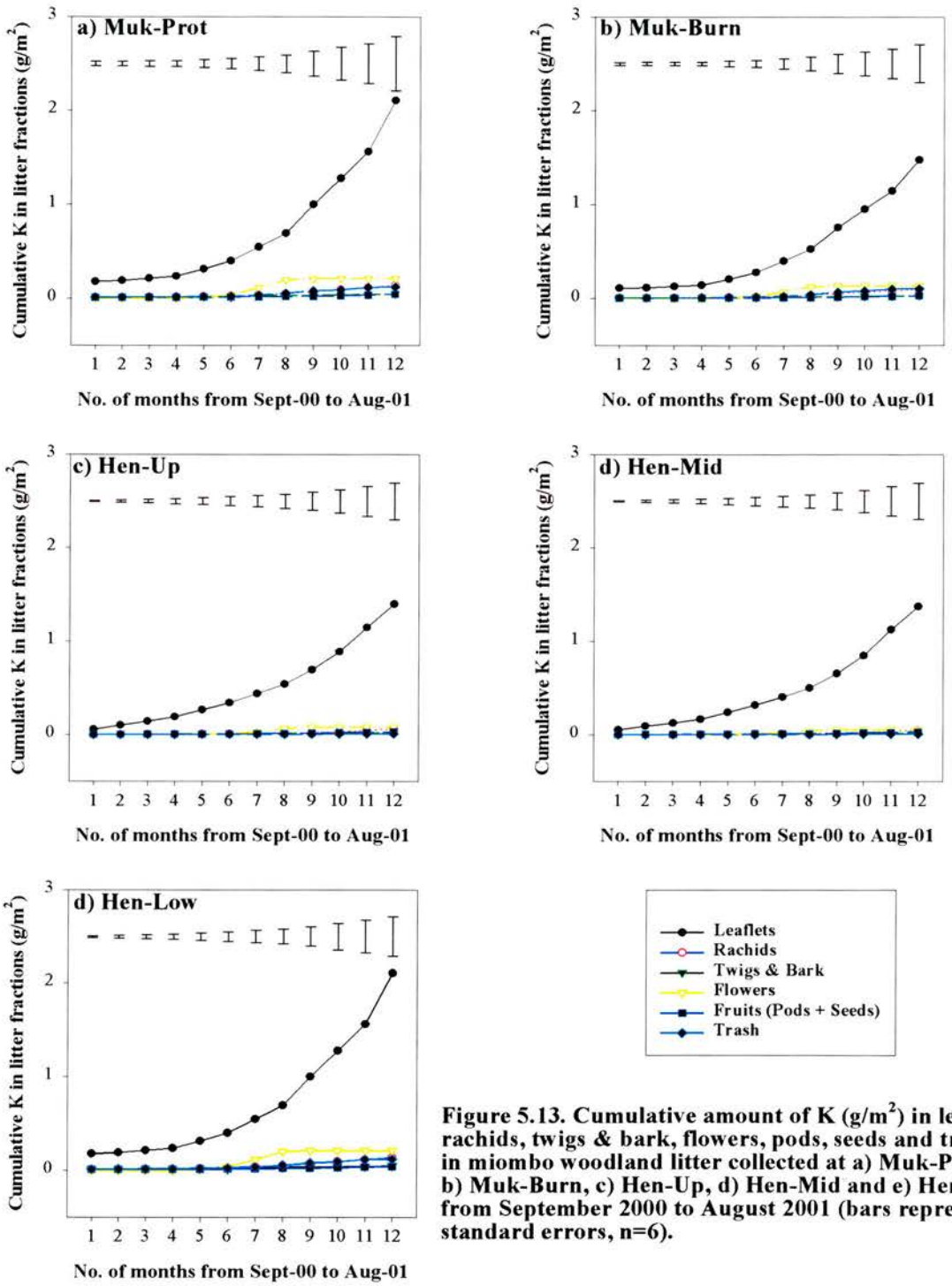


Figure 5.13. Cumulative amount of K (g/m^2) in leaflets, rachids, twigs & bark, flowers, pods, seeds and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

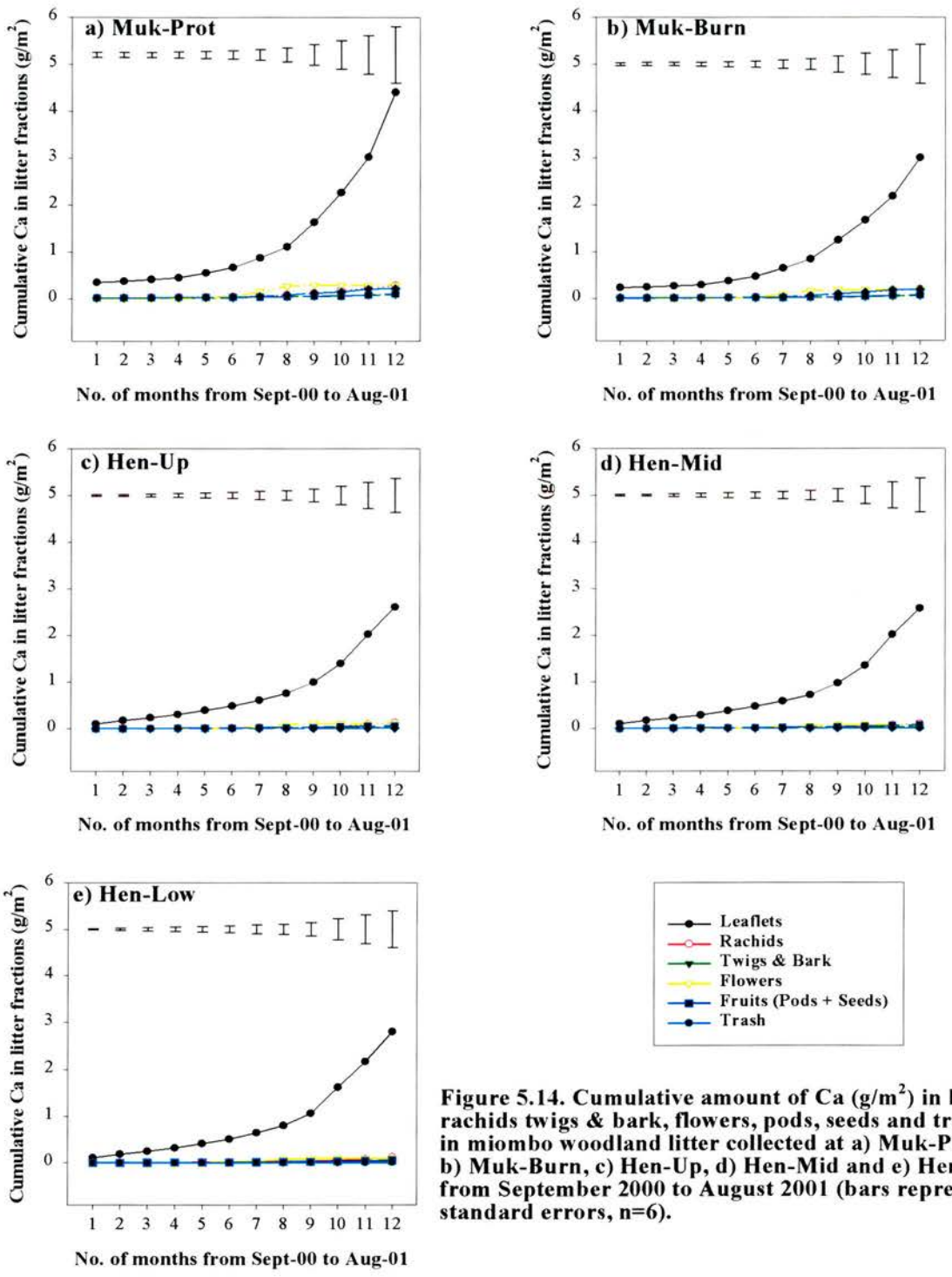


Figure 5.14. Cumulative amount of Ca (g/m^2) in leaflets, rachids twigs & bark, flowers, pods, seeds and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

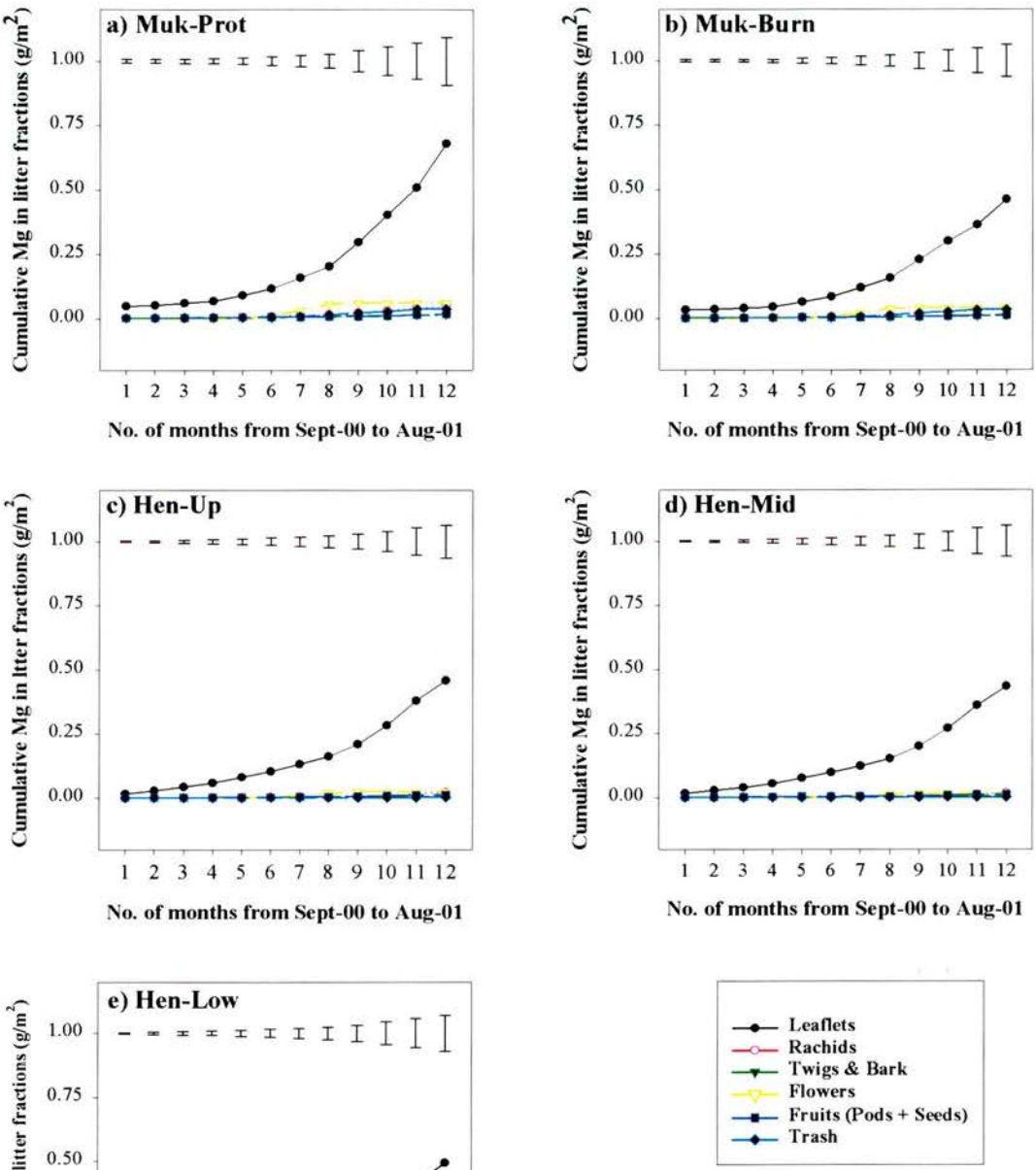


Figure 5.15. Cumulative amount of Mg (g/m^2) in leaflets, rachids, twigs & bark, flowers, pods, seeds and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

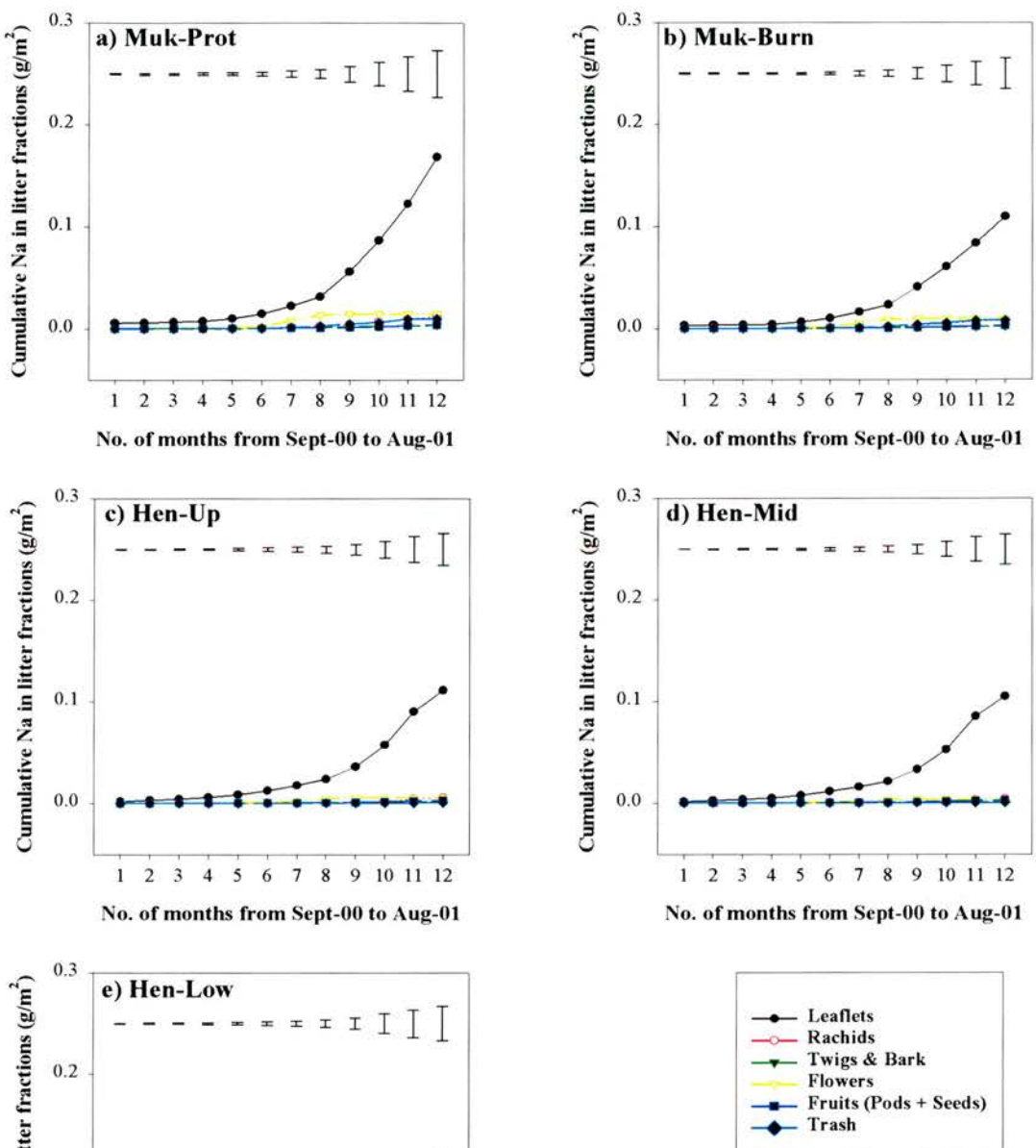


Figure 5.16. Cumulative amount of Na (g/m^2) in leaflets, rachids, twigs & bark, flowers, pods, seeds and trash in miombo woodland litter collected at a) Muk-Prot, b) Muk-Burn, c) Hen-Up, d) Hen-Mid and e) Hen-Low from September 2000 to August 2001 (bars represent standard errors, n=6).

More nutrients were transferred in litter shed at Muk-Prot compared to the other experimental sites (Table 5.5), which directly relate to the higher amount of litter. For all sites, the element with the highest amount of nutrient in litter was N. The amounts recycled in litter from the highest were in the order N > Ca > K > Mg > Na > P.

5.4.3. Litter decomposition

The chemical composition of the litter used in the decomposition experiment is shown in Table 5.6.

Table 5.6 Characteristics of litter used in the litter bag decomposition experiment. Lignin is Acid Detergent Lignin (ADL); hemicellulose is the difference between Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF), polyphenols are condensed tannins

Constituent	% (dry weight)	SE (n = 6)
N	1.69	0.12
P	0.11	0.02
K	0.58	0.06
Ca	1.41	0.07
Mg	0.32	0.05
Na	0.07	0.01
Carbon	51.43	3.26
Lignin (ADL)	33.44	2.14
Cellulose	20.90	2.82
Hemicellulose	7.33	1.30
Polyphenol	4.85	0.61
C:N	31.27	3.01
C:P	502.20	73.29
Lignin/N	20.45	2.29

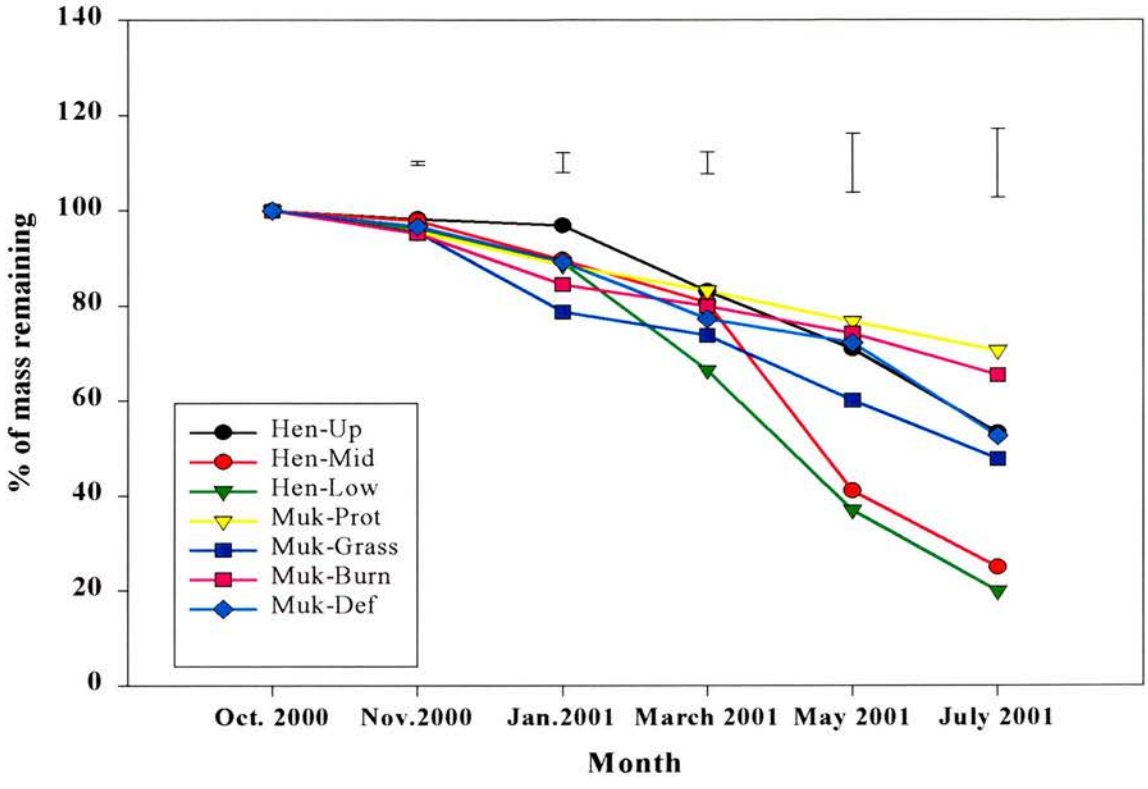


Figure 5.17. % mass remaining of miombo litter during decomposition in litter bags of mesh size 7 mm at Mukuvisi Woodlands and Henderson Research Station experimental sites (bars represent standard errors of means, n = 7).

Mass loss

Decomposition models used by several workers (Olson, 1963; Wieder and Lang, 1982) assume that breakdown of litter and organic matter is exponential. It has, however been observed by others that for a period of a year or less decomposition can follow a linear model (Wieder and Lang, 1982, Tavakol and Proctor, 1994). Of the models tested, mass loss from the litter bags best fit a simple linear model, **y=a+bx** (Fig. 5.17 & Table 5.7) at all experimental areas in the present study. In this model, **y** is the percentage of remaining material from litter bags, **x** is the time elapsed (days), **a** is the intercept and **b** is the slope.

Table 5.7. The relationship between % weight of litter remaining in litter bags (y) and time (days) elapsed (x). Decomposition was found to follow a simple linear model. All values of r are significant ($p<0.001$).

Site	Intercept (a)	Slope (b)	r
Muk-Prot	99.2	-0.11	0.999
Muk-Burn	98.7	-0.12	0.985
Muk-Def	102.0	-0.16	0.964
Muk-Grass	100.0	-0.19	0.989
Hen-Up	105.0	-0.17	0.925
Hen-Mid	109.0	-0.29	0.911
Hen-Low	107.0	-0.31	0.958

Miombo litter decomposition was different at the different experimental sites. The amount of litter remaining after 10 months was highest at Muk-Prot (70 %) (Fig. 5.17). The amount of litter remaining was in the order, Muk-Prot (70 %) > Muk-Burn (65.4 %) > Hen-Up (53.2 %) > Muk-Def > Muk-Grass (47.7 %) > Hen-Mid (24.9 %) > Hen-Low (19.8 %) (Fig. 5.17). The litter bag mesh size of 7 mm allows meso- and macro-fauna access to the litter. In decomposition studies using miombo woodland litter, Musvoto *et al.*, (2000) found 45 % litter remaining after 12 months and this amount fell to 33 % after a

further 6 months. Decomposition at this site is comparable to Muk-Grass and Hen-Up but is higher than Muk-Prot and Muk-Burn and lower than Hen-Mid and Hen-Low. Nyathi (1997) however reports even faster decomposition rates, with less than 20 % litter remaining after only 6 months. In both studies, litter bags were buried in the soil unlike the current study where litter bags were left on the surface.

At Hen-Mid and Hen-Low sites, there was extensive termite activity, which was clearly evident from about March 2001. Termites consumed most of the litter in litter bags at these sites. Hen-Up, which is located on the upper slope did not seem to be affected by termites and therefore decomposition of litter was slower. Termite mounds were only present in Hen-Mid and Hen-Low experiment sites. There was an extensive fire that destroyed almost all the litter on the surface at Henderson sites in early October 2000. Most of the old litter was destroyed and therefore termites immediately used the recently shed litter including that in litter bags. Termite activity was evident towards the end of the rain season (March) and during the dry season. Nyathi (1997) also observed termites foraging litter in buried decomposition litter bags at a site in near Masvingo, 270 km south of Harare. Termites are widespread in miombo woodlands and the dry tropical African region in general where they are involved in nutrient cycling by consuming wood, litter and humus (Trapnell *et al.*, 1976; Dangerfield, 1990 & 1991; Jones, 1990).

At Mukuvisi, limited termite activity was observed at Muk-Grass experimental site. This probably explains why this site had the lowest remaining litter of the Mukuvisi experiment sites. At Muk-Def, no termite activity was observed but after 12 months almost 50 % of the litter had decomposed. There was very little litter on the surface and therefore there was greater interaction between litter and the soil, making the litter more accessible to soil micro-organisms. There was old litter on the woodland floor at Muk-Burn and Muk-Prot, with Muk-Prot having a thicker and more extensive layer because of higher litter production and no burning. Though termite mounds were evident at both Muk-Burn and Muk-Prot, there was no evidence at the sites to suggest that the litter in the litter bags was being foraged by termites. It is possible that there is enough litter on the soil surface, making it unnecessary for the termites to utilise recently shed litter. Thus old litter on the

woodland surface appeared to protect recent litter from termites and from coming into direct contact with soil. Comminution is known to accelerate decomposition (Swift *et al.*, 1981) and at these sites decomposition was relatively slower because of less termite activity.

The late fire at Henderson was caused accidentally. The fireguard protecting this area was not cleared early because of lack of manpower and the political unrest associated with the land re-distribution process in Zimbabwe. The sites had been protected from fire for more than 10 years because they were being used for cattle grazing. Over these years a layer of litter had accumulated on the woodland surface (Table 5.8). The late fire resulted in the complete destruction of herbaceous plant material and most of the litter on the surface. Random litter measurements showed that litter left on the surface ranged from 0 to about 20 % of the average original amount. Herbaceous plant material left ranged from 0 to 10 %. Late fires therefore result in significant loss of nutrients and rapid decomposition of litter.

Litter turnover rate (decomposition constants), k_L

The litter turnover rate or decomposition constant, k_L, has been used by researchers to represent and compare litter turnover for different geographical forest locations (Anderson and Swift, 1983; Scott *et al.*, 1992; Tavakol and Proctor, 1994). Litter turnover rates, k_L, were calculated by dividing the mean annual litter fall (dry weight) by the mean dry weight of small litter on the surface at each site. Values of k_L greater than unity suggest that litter turnover occurs within a year or less and values less than 1 indicate a turnover period of more than a year or several years (Anderson and Swift, 1983). Litter turnover at the two study sites (Table 5.8) were lower than lowland tropical forest decomposition rates, k_L, of 1.1 to 3.3 (Anderson and Swift, 1983). This could be explained by the fact that the woodlands studied are secondary and therefore they are still aggrading. If the woodlands reach "steady-state" (Olson, 1963; Anderson and Swift, 1983) it is likely that the turnover rates might be faster. The small litter turnover rates found fall within the temperate deciduous forests range (from 0.4 to 1.4) (Anderson and Swift, 1983). At the Henderson experiment sites, however, decomposition rates calculated using small litter on the surface

left after the fire was found to be high (Table 5.8). Fire, therefore has a great effect on litter turnover especially after protection for many years resulting in the build-up of fuel load.

Table 5.8. Litter turnover rates (k_L) for litter in miombo woodlands at Mukuvisi Woodlands and Henderson Research Station experimental sites. k_L was calculated by dividing the mean annual litter fall by mean litter standing crop, that is, litter on the soil surface. (AF – After Fire)

Experiment Site	Mean litter standing crop (g/m^2)	Mean annual litter fall (g/m^2)	Litter turnover rate (k_L)
Muk-Prot	809	444	0.55
Muk-Burn	435	301	0.69
Hen-Up	356	237	0.67
Hen-Mid	440	220	0.50
Hen-Low	450	245	0.54
Hen-Up-AF	72	237	3.31
Hen-Mid-AF	60	220	3.65
Hen-Low-AF	63	245	3.86

Nutrient dynamics

Litter decomposition and nutrient release mainly occurs during the rainy season. For all nutrients there was greater loss at Hen-Mid and Hen-Low from about March 2001 because of consumption of litter by termites. The other sites generally had similar nutrient release patterns.

The concentration of N in litter at all the 7 experimental sites initially increased and then declined after about 3 months, approximately at the end of January (Fig. 5.18a). The highest amount of N in litter during the accumulation phase ranged from 108 % at Muk-Grass to 122 % at Muk-Prot. The accumulation of N during the early stage of decomposition has been observed by many workers (Melillo *et al.*, 1982).

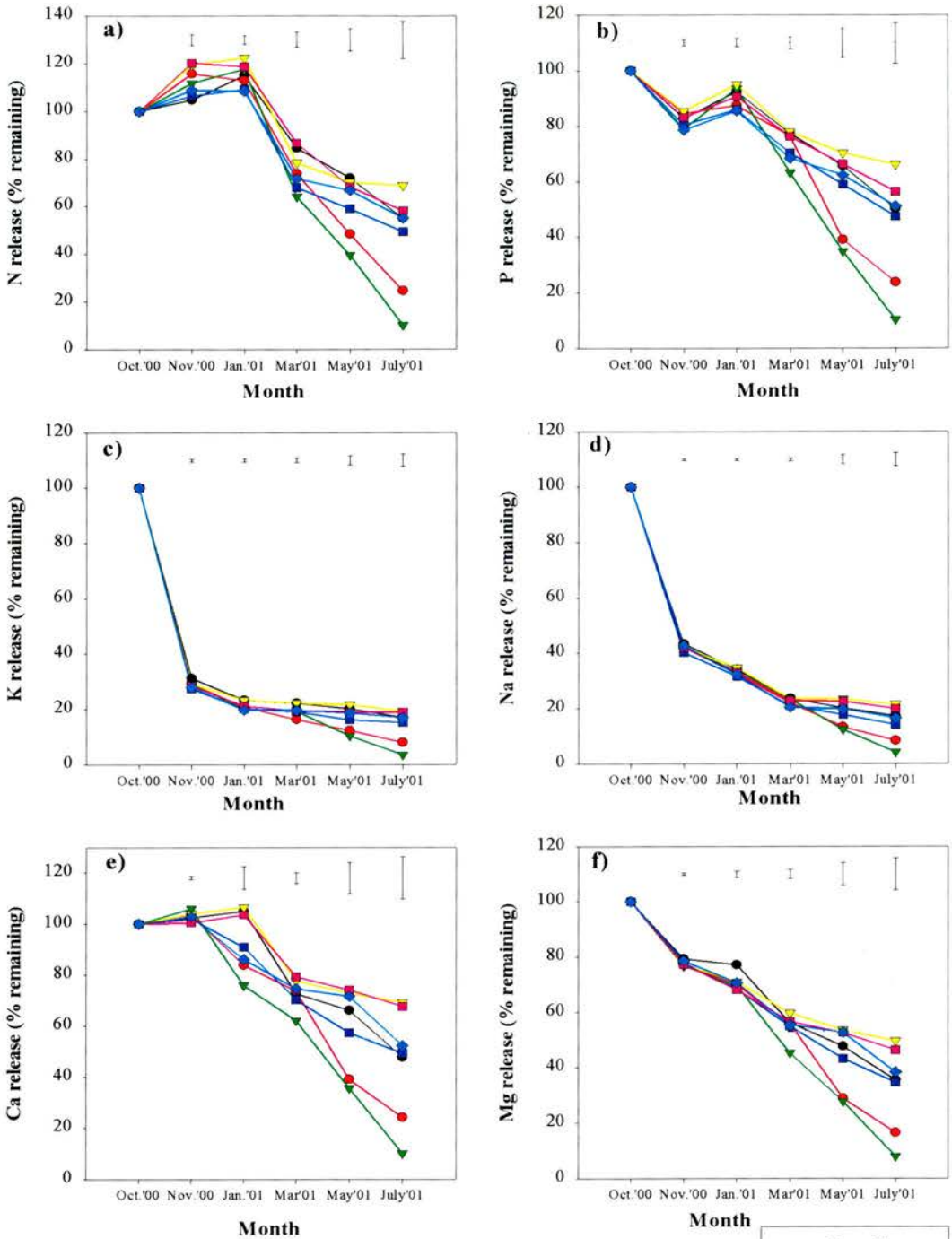


Figure 5.18. Release of a) N, b) P, c) K, d) Na, e) Ca and f) Mgfrom miombo litter in 7 mm decomposition litter bags at Mukuvisi Woodlands and Henderson Research Station experimental sites from October 2000 to July 2001 (bars represent standard errors of the means, n = 7).

Sources of N may include throughfall, dust, insect frass, green litter, fungal translocation and microbial immobilisation (Melillo *et al.*, 1982). Accumulation of N results in a decrease in the C to N ratio of the litter to critical level after which N mineralisation occurs. The C to N ratio can also decrease in the early stages of decomposition without net immobilisation as C is lost by respiration. Gosz *et al.*, (1973) observed that an initial increase in N results in the critical C to N ratio which is generally from 20:1 to 30:1, being reached after which mineralisation occurs. After the accumulation stage, rapid loss was observed at Hen-Mid and Hen-Low sites compared to the other sites mainly because of high termite activity.

Decomposition of litter and release of N is influenced by the initial N and lignin content, C to N and lignin to N ratios (Melillo *et al.*, 1982). Polyphenols also influence N release by binding N containing compounds like proteins (Vallis and Jones, 1973; Palm and Sanchez, 1991). Plant litter with high polyphenol content decomposes slower than litter with low polyphenol contents. In this study, no polyphenols were present in litter at the end of the decomposition experiment. Polyphenols in miombo litter disappear very rapidly during decomposition resulting in minimal effect on the decomposition process (Musvoto *et al.*, 2000).

The initial N content of the litter used was 1.69 % and C to N ratio was 31.27. N mineralisation is known to occur between C to N ratios of between 20 and 30 (Stevenson, 1986). The litter used was marginal in terms of its C to N ratio, which probably explains the initial N immobilisation. Musvoto *et al.* (2000) observed a strong correlation between initial N, lignin content and lignin to N ratio.

Phosphorus decreased during the first month and then increased for the next 2 months Fig. 5.18b). Thereafter, P decreased following the same pattern as N. P in litter at the different sites after about 10 months was in the order Muk-Prot (66.2 %) > Muk-Burn (56.5 %) > Muk-Def (51.2) > Hen-Up (50.2) > Muk-Grass (47.5 %) > Hen-Mid (23.8 %) > Hen-Low (10.3 %). A similar P mineralisation pattern has been observed by other authors (Singh and Shekar, 1989; Rutigliano *et al.*, 1998; Musvoto *et al.*, 2000). P

mineralisation occurs when C to P ratio is less than 300 (Stevenson, 1986). Litter used in the experiment had a C to P ratio of 502.2. This ratio was further increased by the initial leaching of P possibly necessitating immobilisation of P to lower it to a critical level. Gosz *et al.*, (1973) reports that P increased to below a critical C to P ratio after which mineralisation occurs. The C to P ratio can also decrease in the early stages of decomposition without net immobilisation as C is lost by respiration. Initial loss in the first month could be attributed to leaching of soluble P containing compounds, thereafter loss is attributed to decomposition of litter.

Potassium decreased rapidly as also observed by other authors (Singh and Shekar, 1989; Laskowski *et al.*, 1995; Musvoto *et al.*, 2000). K left in litter after about 10 months was in the order Muk-Prot (19.3 %) > Muk-Burn (19.0 %) > Muk-Def (17.1 %) > Hen-Up (17.0 %) > Muk-Grass (15.2 %) > Hen-Mid (8.0 %) > Hen-Low (3.5 %) (Fig. 5.18c). Nutrient loss at a rate higher than mass loss is likely to be due to leaching and nutrients released at a rate equal to or lower than mass loss, are most likely released by decomposition (Gosz *et al.*, (1973). K is highly susceptible to initial loss by leaching because it is not a structural element (Rutigliano *et al.*, 1998). Sodium followed the same pattern of loss of K, though loss was slightly lower (Fig. 5.18d). The amount left in litter however ranged from 4.1 % to 21.4 % of initial nutrient content. Conflicting results on Na leaching have been reported with some authors reporting high rates (Attiwill, 1968; O'Connell, 1988) and others reporting that Na is relatively immobile (Gosz *et al.*, 1973, Laskowski et al., 1995). Such results can be expected because of the differences in litter used with different qualities.

Calcium increased to slightly above the initial amount during the first 3 months and then decreased following the same pattern as mass loss (Fig. 5.18e). Many authors using litter from different vegetation types report a similar pattern (Attiwill, 1968; O'Connell, 1988; Laskowski et al., 1995; Rutigliano *et al.*, 1998; Musvoto *et al.*, 2000). Ca is less susceptible to leaching because it is part of the structural component of the leaf (Gosz *et al.*, 1973). Ca is therefore released less fast than the other cations; its loss rate approximating rate of mass loss (Lisanework and Michelsen, 1994). The amount of Ca

left in litter ranged from 10.1 % (Hen-Low) to 69.2 % (Muk-Prot) (Fig.5.18e) of initial nutrient content.

Magnesium was lost from the litter progressively over time (Fig 5.18f). It was lost slightly faster than Ca, ranging from 49.6 % (Muk-Prot) to 7.9 % (Hen-Low) of initial nutrient content. Mg loss is generally reported to be correlated to mass loss (Rutigliano *et al.*, 1998; Laskowski et al., 1995). In some studies however, some Mg loss is believed to be through leaching (Gosz *et al.*, 1973; Lisanework and Michelsen, 1994). In this study loss of Mg was faster than mass loss suggesting that some Mg is lost through leaching.

5.5. OVERVIEW

Overall there were similarities in nutrient variation in leaves in the dominant miombo tree species. The nutrients N, P, K and Mg were withdrawn from leaves of all the dominant miombo woodland tree species, *J. globiflora, B. spiciformis* and *B. boehmii,* during senescence. P had the highest percentage re-absorbed (48-75 %) indicating that it is possibly the most limiting nutrient in miombo woodlands. N and K may also limit production in miombo woodlands and between 22 to 33 % was reabsorbed at senescence. Mg was only withdrawn in the *J. globiflora* and *B. boehmii* tree species. The nutrients remaining in leaves were transferred to the woodland floor in litter fall. Nutrients locked-up in litter fall become available during decomposition. During decomposition nutrients were released at different rates with K and Na being released faster because they are easily leached.

Overall, the amount of litter and nutrients in litter carried forward to the next season depends on the amount of litter already on the forest floor, the timing of fire events and the rate at which termites consume litter. These factors are linked together intricately. Late fires remove significant amounts of litter on the woodland floor thus also removing food for termites. Termites then consume recently shed litter resulting in rapid decomposition. It is difficult to tell how easily accessible some of the nutrients in termite mounds are to the dominant miombo woodland plants. Some termite mound

builders fix minerals and organic matter and when they abandon their nests hypogeous termites that colonize them cause mineralisation of organic matter (Anderson, 1988; Abbadie *et al.*, 1992). The effect of termites (both mound builders and non-mound builders) needs to be studied and this is an area of potential research. Where there is protection from fire nutrient turnover is slower. The amount of litter carried forward in such cases is higher (> 50 %), resulting in accumulation of litter. Litter is therefore a bank for nutrients N, P Ca and Mg. K is however too low because of leaching losses and this probably explains why miombo trees withdraw K from senescing leaves.

In the next chapter the effect of fire is looked at in detail at Mukuvisi Woodlands where annual early burning is carried out in experiment area Muk-Burn.

6. THE EFFECT OF FIRE ON MIOMBO WOODLANDS NUTRIENT DYNAMICS

6.1. INTRODUCTION

Nutrients are lost from miombo woodlands through seasonal burning. Fire is an important determinant in seasonally dry grasslands and forests, resulting in changes in vegetation structure (Walker, 1985; Bilbao *et al.*, 1996) and nutrient dynamics. African savannas are intimately associated with fires and it is believed that savanna is a fire-determined ecosystem (Gillon, 1983; Menaut *et al.*, 1985). The fire occurs either naturally or through fire management. It is estimated that savannas are burned every 1 to 4 years during the dry season with the areas receiving higher rainfall having the highest frequency because of greater biomass productivity (Frost, 1985b; Crutzen and Andreae, 1990). Many studies on the effects of fire on nutrients have been carried out and they report a loss of nutrients through volatilization, especially nitrogen and sulphur and destruction of organic matter in the upper few centimetres of soil (Mueller-Dombois and Goldhammer, 1990). An increase in exchangeable bases has also been reported (Daubenmire, 1968a; Viro, 1974; Trapnell *et al.*, 1976; Jordan, 1989).

Miombo woodland research has focused on the effect of fire on woody species (Strang, 1974; Chidumayo, 1988; Cauldwell and Zieger, 2000), ash fertilisation from burning miombo biomass (Stromgaard, 1991 & 1992) and effect of fire on soil nutrients (Trapnell *et al.*, 1976). However, more research is needed to assess changes in nutrients not only in soils but also in the herbaceous layer and litter, important components of nutrient cycling in miombo woodlands.

Protecting woodlands from burning results in accumulation of fuel, increasing the risk of a highly destructive fire. It is believed that the best way of protecting and conserving miombo woodlands is by burning early whilst the grass is not too dry (Chidumayo *et al.*, 1996). The effect this woodland management strategy has on nutrient cycling needs to be investigated. At Mukuvisi Woodlands, fire is used as a management tool. Two experimental areas Muk-Burn and Muk-Def are burnt annually early in the dry season,

that is, mid July to early August, so as to prevent the protected areas, Muk-Prot and Muk-Grass from burning. The effect of burning on nutrient dynamics at Mukuvisi Woodlands was therefore investigated.

The objective of the present chapter was to measure the nutrient content of herbaceous plants, litter on the woodland floor and soil before and after burning (in Muk-Prot and Muk-Burn) in order to assess the effect of fire on nutrient cycling in miombo woodlands. It is hypothesized that burning of miombo woodlands results in loss of nutrients especially nitrogen.

6.2. ASSESSMENT OF PREVIOUS RESEARCH INTO THE EFFECTS OF FIRE

6.2.1. Introduction

Savanna fires occur almost exclusively during the dry season and they are either started deliberately by man or may be natural, that is, lightning-induced (Barnes, 1979; Gondo, 1993; Vazquez and Moreno, 1998; Ramos-Neto and Pivello, 2000). Lightning-ignited fires vary in frequency depending on the area (Gondo, 1993; Ramos-Neto and Pivello, 2000). Hilly areas with many granitic rock outcrops are reported to have a higher incidence of lightning induced fires (Vazquez and Moreno, 1998). Fire in savanna areas can also inadvertently result from careless honey gathering (Huntley, 1982).

Fires occurring earlier in the dry season are "cooler", irregular and less damaging to vegetation because some of the vegetation is not too dry (Hiernaux and Diarra, 1985). Controlled dry season burning is therefore used in the savannas as a management tool earlier at the beginning of the dry season to prevent hotter, intense and more damaging fires latter in the dry season (Crutzen and Andreae 1990; Whelan, 1995; Bond and van Wilgren, 1996). Such fires serve mainly to reduce dry, dead plant material accumulation in woodlands and forests. In many savanna regions of the world, fire is considered a valuable tool in livestock production and wildlife management, encouraging new growth of grass and preventing bush encroachment in grazing areas (Trollope, 1982). It is also an important tool for controlling ticks (Kayll, 1974; Trollope, 1982).

6.2.2. Effect of fire on vegetation

Savanna fires are generally restricted to the herbaceous layer (ground fires) and crown fires rarely occur (Walker, 1985). Fire has variable effects from one point to another and from year to year and is often patchy (Frost, 1985b). It has the effect of controlling the build-up of woody species (Johnson and Tothill, 1985). Seasonal forest fires in southern Africa cause degradation of indigenous woodlands through killing saplings, young seedlings and small woody plants, scarring large trees and destroying microfauna and litter (Frost, 1985b; Walker, 1985; Temu, 1993). Trees and shrubs suffer the greatest damage when burnt during the early stages of leaf development (West, 1969; Kennan, 1971). Intermediate size woody plants are suppressed in semi-arid and mesic savannas resulting in a "parkland" (Huntley, 1982) and Hooper (1985) reports reduction in density in Australian savanna woodlands. Fire can push community succession in the direction of low plant biomass (Bell, 1982) and persistent and frequent fires cause destruction of plant communities resulting in an equilibrium of more fire-tolerant vegetation species (Trollope, 1982; Menaut *et al.*, 1985, Temu, 1993). Fire protection on the other hand increases species diversity and grasses change to open woodland and ultimately to dry deciduous woodlands or forests (Yeaton, 1988).

The effect of fire on vegetation is determined by fire intensity, fuel load, timing of the fire and other environmental factors such as prevailing weather conditions (Trollope, 1980; Frost, 1985b, Whelan, 1995). Fire intensity depends on distribution of fuel, wind speed and direction (Whelan, 1995). Fire temperature varies spatially and Sweet and Tacheba (1985) report mean temperatures in savanna fires measured with thermo-crayon strips of up to 640 ± 11°C. Maximum temperatures that can be attained in these fires vary in space and duration and may be up to 1150°C (Ewusie, 1980). Grass-fuelled fires are generally mild reaching a height of about 2 metres and high intensity wild fires can have an effect up to a height of 7 metres (Hooper, 1985). Survival of individual plants and plant species in a particular fire depends on the intensity and high intensity fires tend to be very destructive (Whelan, 1995).

Most savanna fires are grass-fuelled and a higher fuel load of dry grass results in hotter and intense fires that can kill many woody plants. Higher biomass production is found in savanna areas receiving higher rainfall (>750 mean annual rainfall). Fire frequency therefore decreases with decreasing rainfall, ranging from an annual event in humid savannas to occasional and irregular in most arid areas (about 1 in 20 years) (Walker, 1985; van Wilgen *et al.*, 1990). Where fire frequency is high, plant species tend to be more adapted to fire (Medina, 1982; Frost, 1985b; Menaut *et al*, 1985). Adaptation ranges from selection of niches that seldom burn, dormancy during the main fire season, tolerance of fire, seed burial and hypogeal germination and ability to regenerate from seed where plants cannot withstand fire (Bond and van Wilgen, 1996). Trollope (1982) observed that some southern African savanna tree and shrub species are very resistant to fire due to dormant protected buds at the base of the stem from which coppicing occurs. Similar characteristics are also found in many grasses and geophytes (van Wilgen *et al.*, 1990; Bond and van Wilgen, 1996).

6.2.3. Effect of fire on nutrients

Research on wild fires has been driven mainly by the need to control fires (Bond and van Wilgen, 1996), understanding the ecology of fire and the properties that allow plants to burn, how and when they burn and to assess the effect of biomass burning on atmospheric chemistry (Crutzen and Andreae, 1990).

In southern Africa a few long-term experiments have been established to study the effect of fire savanna vegetation (Trapnell, 1959; Barnes, 1965; Kennan, 1971; Strang, 1974). The experiments were established to investigate the effect of early and late burning on miombo tree growth (Trapnell, 1959), the effect of fire on vegetation during different seasons and at different frequencies (Kennan; 1971), and the effectiveness of fire, grazing and mattoking in controlling miombo tree re-growth (Barnes, 1965; Strang, 1974). The effect of fire on soils was not the major objective of these experiments and therefore changes in soil properties were not monitored from the beginning of trials but were studied many years later (Trapnell *et al.*, 1976; Tsvuure, 1997). In long term fire experiments burning is carried out regularly whereas natural savanna ecosystems do not

burn on a regular basis (Chidumayo, 1989). This situation has been changing because with the interference of man, several fire prone savanna ecosystems are being burnt regularly (Eldroma, 1984) making long-term fire experimentation invaluable. Studies of one-off, occasional fires are also necessary to broaden our understanding of fire on savanna vegetation and nutrient cycling. Other studies on the effect of fire on nutrients in miombo woodlands in southern Africa have been carried out in relation to ash fertilization in shifting cultivation (Stromgaard, 1991 & 1992) and effect of wood carbonization on soil properties (Chidumayo, 1994). More studies are needed in this area because there are still gaps in our understanding of the effect of fire on nutrient cycling in miombo woodlands. Burning has been observed in southern Africa and elsewhere in the world to increase most plant nutrients in topsoils (DeBano and Conrad, 1978; Lewis, 1974; Stromgaard, 1991 & 1992). The increase of nutrients in soil comes from litter, herbaceous and some woody plants burnt during the fire. Soils have been shown to have marked increases in exchangeable bases especially Ca and Mg (Daubenmire, 1968b; Viro, 1974; DeBano and Conrad, 1978; Woodmansee and Wallach, 1981; Jordan, 1989). Fire has a detrimental effect on soil fauna (Menaut *et al*, 1985; Dumontet *et al.*, 1996). Some researchers have however observed an enhancement of microbial cycling of N after fires (Woodmansee and Wallach, 1981; Crutzen and Andreae, 1990). Increased microbial activity after burning could be attributed to structural vulnerability of litter after burning (Ahlgren and Ahlgren, 1965).

Litter on the forest floor is an important reservoir of nutrients, which releases nutrients slowly and holds them against loss and in miombo woodlands litter is a major nutrient cycling pathway (Chapter 5). Burning of litter may render some nutrients volatile, water soluble or susceptible to suspension in air as fine particulate matter, and over long periods may result in a reduction in soil fertility (Lewis, 1974; Medina, 1982; Hiernaux and Diarra, 1985; Ward, 1990). A study of effect of fire on nutrient cycling should therefore include changes in nutrients in litter on the surface. Severe fires can also result in destruction of soil organic matter and mild fire can result in increased organic matter (Raison, 1979). Fire also causes seasonal mineralisation of nutrients especially of N and

hydro-soluble organic matter and these are integrated into the soil by the rains (Menaut *et al.*, 1985).

Burned litter holds less water and may lose more nutrients to leaching. Lewis (1974) found that the amount of Ca, Mg, Na and K lost during natural leaching and runoff is greater after burning. Biomass burning, like the burning of litter, may result in loss of nutrients in gaseous form and in smoke particles and in loss of up to 50 % N in biomass fuel (Crutzen and Andreae, 1990). During a fire nitrogen is lost as N_2, NO, N_2O, NH_3, HCN and CH_3CN gases (Crutzen and Andreae, 1990). Substantial amounts of N from litter, plants and soil surface layer can be lost if temperatures are very high (> 700°C) (DeBano and Conrad, 1978).

The effect of fire on nutrient cycling is complex (Raison, 1979; Medina, 1982; Walker, 1985). To understand the effect of burning on nutrient changes in miombo woodlands there is need to monitor changes in the three components, litter, soil and herbaceous plant material, that are affected by fire. Many workers (Henzell, 1985; van Wilgen *et al.*, 1990) have highlighted the need for information on the role of fire in the functioning of savanna ecosystems, especially in nutrient cycling. There is no documented research on the effect of fire on herbaceous plant material and litter in miombo woodlands and the impact on nutrient cycling.

6.3. MATERIALS AND METHODS

Herbaceous plants were harvested from 1 m^2 quadrats randomly located at about 40 m apart along transects at Henderson Research Station and Mukuvisi Woodlands. At Mukuvisi Woodlands, Muk-Prot, Muk-Burn and Muk-Grass had each a total of 21 quadrats, 7 along each transect. Muk-Def had only 7 quadrats. Each experimental site at Henderson had a total of 6 quadrats, 2 along each transect. Fewer quadrats were identified at Henderson experimental areas because the transects were smaller than at Mukuvisi Woodlands.

Herbaceous plant material was carefully harvested 2.5 cm above the ground using a sickle in June/July, 2001. Litter on the soil surface was collected from the 1 m^2 quadrats after harvesting standing herbaceous plant material. Litter and herbaceous plant material was dried in an oven at 60 °C for 3 days, weighed and analysed for total N, P, Ca, Mg, K and Na using methods described in section 2.2.3.

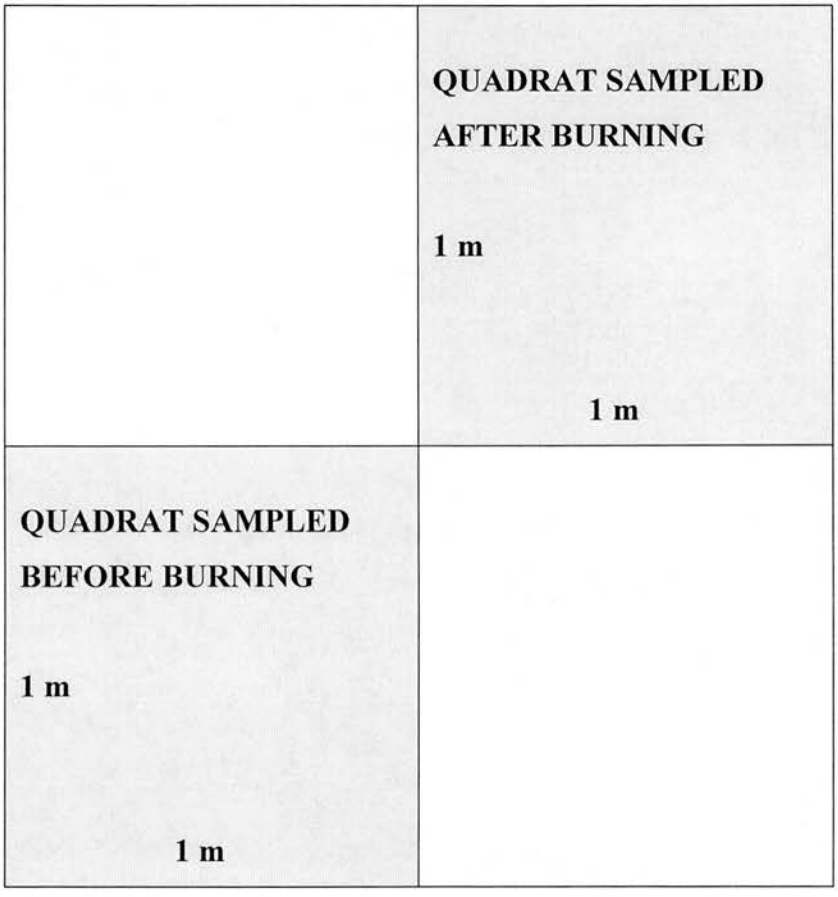


Figure 6.1. Quadrats sampled for herbaceous plant material, litter on the surface, and soil samples before and after burning at Muk-Burn and Muk-Def experimental sites.

Soils samples were also collected from the quadrats after harvesting and litter collection. Small pits 30 cm x 30 cm and 40 cm deep were dug. Soil samples were collected carefully from cleaned opposite sides from depths, 0-3 cm, 3-6 cm, 6-10 cm, 10-20 cm and 20-30 cm. Soils from the same depths from the opposite sides were mixed to make a composite sample. Composite samples were air dried, ground and sieved to pass through a 2 mm sieve. They were then analysed for microbial C and N, total C, N, P, Ca, Mg and K using methods described in section 2.2.2.

At the Muk-Burn and Muk-Def experimental sites controlled burning was carried out during the first two weeks in August 2001. Herbaceous plant material, litter and soil samples were similarly collected within about a week after burning (Gillon and Rapp, 1989), from diagonally opposite quadrats (Fig. 6.1). Therefore at Muk-Burn and Muk-Def experimental sites, herbaceous plant material, litter and soil samples were collected before and after burning to understand the effect of fire nutrients. Gillon and Rapp (1989) carried out a similar study in a Mediterranean forest.

Nutrient contents before and after burning at Muk-Burn and Muk-Def in standing herbaceous plant material, litter on the surface and in the top 30 cm of the woodland soils were analyzed using a Paired-T test to assess the immediate effect of fire. The effect of fire on nutrients over 13 years was tested by comparing the burnt areas with the protected areas. The data was analysed using ANOVA to test if burning has had a significant effect on soil nutrients.

6.4. RESULTS AND DISCUSSION

6.4.1. Nutrients in herbaceous plant material

Burning at Muk-Burn resulted in the loss of 96.1 % of standing herbaceous plant biomass. The amount remaining was significantly lower than the amount before burning ($p<0.001$). At Muk-Def, the amount of standing herbaceous plant biomass was significantly lower ($p < 0.01$) than the amount before burning. The standing herbaceous plant material lost through burning was 86.4 %. As expected, a high amount of the

herbaceous layer was burnt because savanna fires are mainly grass fuelled (Walker, 1985; van Wilgen *et al.*, 1990). During the month of August, a lot of herbaceous plants had low moisture content, hence very high proportions of herbs were completely burnt. Generally, the early dry season is from the beginning of July to mid August. The peak of the dry season when fires are very destructive, both to herbaceous and woody plants, is the month of October. However, from the results, it is evident that a high proportion of herbs were destroyed and therefore, mid-July was possibly the best month if one wanted to destroy fewer herbaceous plants. Timing of managed fires should depend on when the rain season ends. The 2000/2001 rainy season ended early in March 2001 hence by August 2001 most of the herbaceous plants were dry. Field observations showed that the fire affected large trees much less severely. On the other hand, small trees and shrubs less than 2m height were severely affected by fire. These results indicate that the fire was of low intensity. Low intensity fires are classed as those with an average flame height of about 1.5 m (Cheney, 1981) and Kennan (1971) defined them as fires affecting trees of height less than 1.8 m.

Nutrient concentration and amount of nutrients per m^2 in herbs at Mukuvisi Woodlands and Henderson Research Station are shown in Tables 6.1 and 6.2 respectively. Table 6.2 also shows the nutrients lost from herbaceous plant material at the burnt experimental areas, Muk-Burn and Muk-Def. At Henderson Research Station there were no burning treatments and measurements were made to compare with results from Mukuvisi Woodlands experimental areas Muk-Prot, Muk-Burn-BB (that is, before burning) and Muk-Def-BB (that is, before burning). The immediate effect of burning on nutrients was assessed by comparing the amounts in herbaceous plants before and after burning at Muk-Burn and Muk-Def. The significance of the difference between before and after burning was tested using a Paired-T test (Ryan and Joiner, 2001). Burning resulted in significant nutrient losses from herbaceous plants. Nutrient concentration (%) (Table 6.1) at Muk-Burn-BB was significantly higher than Muk-Burn-AB ($p>0.001$) for the nutrients N, Ca, Mg, K and Na. There was no significant difference in the concentration of P. Nutrient concentration results indicate that fire significantly altered the nutrient concentration of the remaining herbaceous plant material. DeBano and Conrad (1978)

however point out that evaluation of the effect of fire should be on the basis of weight loss per unit area to avoid erroneously concluding that fire did not have an effect. Comparison of Muk-Burn-BB (that is, before burning) and Muk-Burn-AB (that is, after burning) using Paired-T Test showed highly significant ($p<0.001$) difference in total nutrients (g/m^2) N, P, Ca, Mg, K and Na. Results are in agreement with other workers who have reported significant nutrient loss from grass fires (Gillon and Rapp, 1989).

Nutrient concentration (%) (Table 6.1) before and after burning, that is, Muk-Def-BB and Muk-Def-AB respectively, was significantly different ($p<0.01$) for the nutrients N, Ca, Mg, K and Na. There was however no significant difference in P concentration before and after burning at Muk-Def. Total nutrients (g/m^2) N, Ca, Mg, K and Na at Muk-Def-BB were significantly higher ($p<0.01$) than Muk-Def-AB. Total nutrient (g/m^2) P was significantly higher ($p>0.05$) at Muk-Def-BB than Muk-Def-AB. Some of the nutrients like N are lost in gaseous form (Crutzen and Andreae, 1990) and some are lost as particulate matter in smoke (Ward, 1990; Lewis, 1994). However, some nutrients from burnt plants are deposited on the soil surface and they may be incorporated into the soil by rainfall resulting in elevated nutrient contents in surface soils (DeBano and Conrad, 1978).

The effect of burning a miombo woodland for about 13 years was assessed by comparing Muk-Burn-BB with the other Mukuvisi experiment areas Muk-Def-BB, Muk-Prot and Muk-Grass. Experimental sites Muk-Burn-BB, Muk-Def –BB and Muk-Grass had no significant difference ($p<0.05$) in the amount of herbaceous plant biomass. Muk-Grass and Muk-Burn had significantly higher ($p<0.001$) amount of herbaceous plant biomass than Muk-Prot. It was expected that Muk-Prot, the protected miombo woodland, would have less herbaceous biomass because of the relatively higher tree density. It appears that over the years fire has reduced tree density (Chapter 3) of the burnt woodland, Muk-Burn, allowing more grass species to establish. Frequent fires in savanna woodlands push succession towards more open woodland with a higher grass biomass (Bell, 1982, Yeaton, 1988). Muk-Grass, which was expected to have even

Table 6.1. Above ground herbaceous biomass (g/m^2) and nutrient concentration (%) in herbaceous plant material from Mukuvisi Woodlands and Henderson Research Station experiment sites. Only experimental areas Muk-Burn and Muk-Def were subjected to the burning treatment (SE- Standard Error; BB – Before Burning; AB – After Burning).

Experiment Site	Herbs (g/m^2)	SE	% N	SE	% P	SE	% Ca	SE	% Mg	SE	% K	SE	% Na	SE
Muk-Burn-BB	228	30	0.78	0.07	0.26	0.02	1.13	0.09	0.29	0.03	1.03	0.10	0.22	0.03
Muk-Burn-AB	9	5	0.10	0.03	0.24	0.07	0.09	0.03	0.07	0.02	0.30	0.09	0.05	0.01
Muk-Def-BB	168	18	0.64	0.06	0.22	0.02	1.08	0.09	0.26	0.02	1.00	0.05	0.28	0.02
Muk-Def-AB	23	3	0.21	0.02	0.49	0.05	0.16	0.03	0.11	0.01	0.29	0.04	0.09	0.01
Muk-Prot	105	10	0.81	0.10	0.25	0.03	1.10	0.10	0.27	0.02	1.06	0.11	0.27	0.02
Muk-Grass	335	40	0.82	0.08	0.24	0.03	1.15	0.09	0.31	0.03	0.97	0.09	0.23	0.02
Hen-Up	165	30	0.74	0.07	0.30	0.02	1.31	0.09	0.32	0.02	1.25	0.08	0.22	0.03
Hen-Mid	249	31	0.68	0.07	0.31	0.03	1.35	0.06	0.31	0.03	1.39	0.07	0.22	0.03
Hen-Low	226	37	0.72	0.08	0.27	0.03	1.42	0.09	0.32	0.02	1.15	0.08	0.23	0.03

Table 6.2. Mean total nutrient content (g/m^2) in herbaceous plant material from Mukuvisi Woodlands and Henderson Research Station experiment sites. The rows in the table with nutrient losses from Muk-Burn and Muk-Def have been highlighted by shading. Losses may be transferred to the soil surface or lost in smoke as particulate matter. (SE- Standard Error; BB – Before Burning; AB – After Burning).

Experiment Site	Herbs (g/m^2)	SE	Total N (g/m^2)	SE	Total P (g/m^2)	SE	Total Ca (g/m^2)	SE	Total Mg (g/m^2)	SE	Total K (g/m^2)	SE	Total Na (g/m^2)	SE
Muk-Burn-BB	228	30	1.79	0.34	0.59	0.10	2.71	0.52	0.64	0.10	2.36	0.42	0.53	0.10
Muk-Burn-AB	9	5	0.02	0.02	0.04	0.02	0.03	0.02	0.02	0.02	0.08	0.05	0.01	0.01
Muk-Burn-Losses	**218**		**1.77**		**0.55**		**2.68**		**0.62**		**2.28**		**0.52**	
Muk-Def-BB	168	18	1.02	0.14	0.40	0.08	1.66	0.18	0.43	0.05	1.59	0.13	0.44	0.05
Muk-Def-AB	23	3	0.05	0.01	0.12	0.03	0.03	0.01	0.03	0	0.05	0.01	0.02	0
Muk-Def-Losses	**145**		**0.97**		**0.28**		**1.63**		**0.40**		**1.54**		**0.42**	
Muk-Prot	105	10	0.83	0.12	0.28	0.05	1.13	0.13	0.29	0.04	1.04	0.13	0.28	0.04
Muk-Grass	335	40	2.78	0.51	0.86	0.18	3.75	0.54	0.99	0.15	3.29	0.62	0.75	0.11
Hen-Up	165	30	1.03	0.12	0.54	0.14	1.95	0.29	0.44	0.05	1.88	0.28	0.29	0.04
Hen-Mid	249	31	1.97	0.41	0.77	0.13	3.39	0.42	0.82	0.15	3.29	0.40	0.56	0.09
Hen-Low	226	37	1.72	0.31	0.62	0.13	3.68	0.77	0.68	0.10	2.84	0.61	0.58	0.11

higher herbaceous plant biomass did not have significantly higher amounts possibly because of grazing by wild animals. Compared to the Henderson experimental sites the amounts of herbaceous plant biomass at the Mukuvisi sites were not significantly different ($p<0.05$).

6.4.2. Nutrients in litter

Burning resulted in the loss of 37.1 % of litter on the surface at Muk-Burn. Litter before and after burning was not measured at Muk-Def because this experiment area is deforested. Coppicing trees are continually removed from Muk-Def because a high voltage powerline passes through this area. The Paired-T Test showed that the difference in the amount of litter at Muk-Burn before and after burning was highly significant ($p<0.001$).

N concentration (Table 6.3) in litter sampled at Muk-Burn was significantly ($p < 0.05$) higher before burning compared to after burning. However, for the other nutrients, P, Ca, Mg, K and Na, there were no significant differences in nutrient concentration before and after burning. Many workers (Crutzen and Andreae, 1990; Ward, 1990) have pointed out that N is easily lost in gaseous form during burning. The other nutrients, P, Ca, Mg, K and Na may remain in ash and in partially burnt litter on the soil surface (DeBano and Conrad, 1978) and some amount may be lost in smoke as particulate matter. Some of the nutrients measured in litter may include nutrient deposits from burnt herbaceous plant material.

Total nutrients in litter (g/m^2) (Table 6.4) collected from 1 m^2 quadrats before and within a week after burning were compared using a Paired-T Test. The difference in total N and Na between Muk-Burn-BB and Muk-Burn-AB was highly significant ($p <0.001$). Total Mg ($p < 0.01$), K ($p < 0.01$) and P ($p < 0.05$) were significantly higher at Muk-Burn-BB than Muk-Burn-AB. The difference in Ca was however not significant ($p < 0.05$). Gillon and Rapp (1989) also report a non-significant loss of Ca from a burnt Mediterranean forest fuel.

Table 6.3. Nutrient concentration (%) in litter from Mukuvisi Woodlands and Henderson Research Station experiment sites. (SE - Standard Error; BB – Before Burning; AB – After Burning).

Experiment Site	Litter (g/m^2)	SE	% C	SE	% N	SE	% P	SE	% Ca	SE	% Mg	SE	% K	SE	% Na	SE
Muk-Burn-BB	692	65	43.7	1.9	0.77	0.05	0.08	0.01	0.30	0.03	0.12	0.01	0.12	0.02	0.06	0
Muk-Burn-AB	435	54	36.7	2.1	0.66	0.05	0.09	0.01	0.38	0.05	0.14	0.02	0.12	0.02	0.06	0
Muk-Prot	809	80	46.5	1.4	0.80	0.05	0.09	0.01	0.32	0.03	0.15	0.02	0.14	0.02	0.06	0
Hen-Up	356	46	47.5	1.2	0.90	0.06	0.07	0.01	0.26	0.04	0.09	0.01	0.24	0.03	0.05	0
Hen-Mid	440	23	45.3	1.8	0.97	0.05	0.08	0.01	0.37	0.03	0.10	0.01	0.15	0.02	0.06	0.01
Hen-Low	450	34	43.7	1.3	0.84	0.03	0.07	0.01	0.38	0.03	0.11	0.01	0.11	0.01	0.06	0

Table 6.4. Mean total nutrient content (g/m^2) in litter at Mukuvisi Woodlands and Henderson Research Station experiment sites. The row with nutrient losses from litter at Muk-Burn is highlighted with shading. (SE - Standard Error; BB – Before Burning; AB – After Burning).

Experiment Site	Litter (g/m2)	SE	Total N (g/m2)	SE	Total P (g/m2)	SE	Total Ca (g/m2)	SE	Total Mg (g/m2)	SE	Total K (g/m2)	SE	Total Na (g/m2)	SE
Muk-Burn-BB	692	65	5.49	0.65	0.55	0.08	2.05	0.32	0.82	0.11	0.87	0.13	0.43	0.04
Muk-Burn-AB	435	54	2.93	0.48	0.34	0.05	1.47	0.22	0.54	0.07	0.48	0.07	0.27	0.03
Muk-Burn-Losses	**257**	**61**	**2.56**	0.51	**0.22**	0.08	**0.58**	0.33	**0.28**	0.09	**0.39**	0.12	**0.16**	0.04
Muk-Prot	809	80	6.44	0.80	0.73	0.12	2.62	0.35	1.17	0.17	1.14	0.21	0.51	0.05
Hen-Up	356	46	3.49	1.14	0.28	0.10	1.05	0.42	0.29	0.06	0.82	0.21	0.19	0.05
Hen-Mid	440	23	4.26	0.62	0.35	0.06	1.66	0.32	0.41	0.06	0.64	0.15	0.29	0.06
Hen-Low	450	34	3.78	0.57	0.29	0.06	1.79	0.40	0.46	0.08	0.49	0.07	0.28	0.05

Litter samples from Muk-Burn-BB were compared with the unburnt woodland sites at Mukuvisi Woodlands and Henderson Research Station, Muk-Prot, Hen-Up, Hen-Mid and Hen-Low sites. Total nutrients N, P, Ca, Mg, K and Na, (Table 6.4) were not significantly different with the exception of Mg and Na at Muk-Prot compared to Hen-Up which were significantly different ($p < 0.05$ and $p < 0.01$ respectively).

From the results, early burning seems to have immediate major effect on herbaceous plant material resulting in loss and transfer of nutrients most likely to the surface of the soil and atmosphere as aerosols. In the case of litter, only N is significantly affected by burning confirming the hypothesis that nitrogen is the main nutrient affected by fire. Many workers report large losses of N through fire and they attribute this loss mainly to volatilisation (Ward, 1990; Mackensen *et al.*, 1996). However, more N could have been lost if the fire occurred during the latter part of the dry season. From the amount of litter burnt, it can be inferred that temperatures reached on the soil surface were low. Raison (1979) reports that very high temperatures of around 700 ^{o}C are required to destroy all the litter on the surface. Woodmansee and Wallach (1981), however, describe hot-burn fires capable of consuming all litter on the surface if sustained for long enough as those with temperatures greater than 300^{o}C.

6.4.3. Soil nutrients

The % total amounts of organic C, N, P, Ca, Mg and K were highest in the top 10 cm depth (Figure 6.2 & 6.5) for the Mukuvisi and Henderson sites with the exception of Mg at Muk-Burn where there was higher Mg in the 20-30 cm depth range (Figure 6.5e). Nutrient contents in the 0-3, 3-6, and 6-10 cm depth ranges were higher possibly because of the higher amounts of organic matter (higher organic carbon) (Figures 6.2a & 6.5a). Splitting of the top 10 cm into horizons 0-3, 3-6 and 6-10 cm showed that the top 0-3cm depth has the highest % total organic C and the other nutrients measured (Figure 6.2-5).

The effect of burning was investigated at Mukuvisi Woodlands experiment sites, Muk-Burn and Muk-Def. The % total microbial biomass C and N, % total organic C, N, P,

Ca, Mg and K were measured before burning and within a week after burning. Results were analysed using a paired T-test. % Microbial biomass C and N before and after burning at Muk-Burn and Muk-Def (Figure 6.3 a & b) were not significantly different ($p < 0.05$). These results indicate that temperature of top soils did not rise markedly during the fire to affect soil microbes. Soil temperature during a fire is variable and depends on fuel distribution, moisture content and prevailing weather conditions. Soil temperature within the top 6 cm depth may range from 40 °C to 100°C (Raisin, 1979). Dumontet *et al.* (1996) however reports a decline in microbial biomass and they observed that fire had long term effects on soil microbiological properties in a pine forest in a Mediterranean environment. Elsewhere it was reported that microbial biomass is markedly reduced by fire but after the fire there is rapid microbial activiy (Woodmansee and Wallach, 1981). This could explain the increase in ammonium nitrogen observed by Jordan (1989) after burning. In this study soils were collected about 5 days after the fire and in this period there could have been some microbial activity which could mask the immediate effect of fire.

The % total organic C was higher after burning at Muk-Burn and Muk-Def (Figure 6.2a). Raison (1979) reports that mild fires can result in an increase in organic C because of partial burning of herbaceous plants and litter. Higher C contents are due to ash from the burnt herbaceous plants and litter (Crutzen and Andreae, 1990; Stromgaard, 1991). It is however possible that part of the measured increase in % total organic C may be due to inorganic elemental C from burnt plant material. Muk-Burn-AB after burning (2.72 ± 0.843 %) had significantly higher ($p<0.01$) % total organic C than Muk-Burn before burning (1.86 ± 0.642 %). These results are in agreement with other workers' observations that burning does not necessarily destroy soil organic matter (Andriesse and Schelhaas, 1987; Stromgaard, 1991). At the end of the rain season, it is likely that there is a decrease in organic C as small organic particles may be mechanically eluviated down the profile (Stromgaard, 1991). However, there was no significant difference in % total organic C in the 3-6 and 6-10 cm depth ranges. The difference in % total organic C in Muk-Def after burning (1.5 ± 0.396 %) and before burning (1.23 ± 0.100 %) was not significant ($p<0.05$) for the 3 depth ranges (0-3, 3-6

and 6-10 cm). No significant difference in % total N before and after burning was observed for the depth ranges 0-3, 3-6 and 6-10 cm in the two sites Muk-Burn and Muk-Def.

After burning, % total P (0.03 ± 0.010 %) was significantly higher ($p<0.01$) at Muk-Burn 0-3 cm depth than before burning (0.02 ± 0.011 %). However, in the 3-6 and 6-10 cm depth range there was no significant difference in % total P after burning. From these results fire seemed to significantly increase % total P only in the top 3 cm depth. Stromgaard (1992) found substantial immediate increases in available P in topsoil after burning of miombo tree biomass. At Muk-Def, there was no significant difference in % total P between before and after burning in the 0-3 and 3-6 cm depth range. However there was a significant increase ($p<0.05$) in % total P at Muk-Def in the 6-10cm depth after burning. The observed increase in P in burned topsoil at Muk-Burnt is consistent with findings on annually burned savannas (Trapnell *et al.*, 1976; Brookman-Amissah *et al.*, 1980). Many however report that the increase in P is attributed to heating and is short-lived and normally the increase is followed by a decline in P (Humphreys and Craig, 1981; Dumontet *et al.*, 1996). Others report a minor immediate effect of fire on P (Kauffman *et al.*, 1993).

Burning had no immediate statistically significant effect on % total Ca, Mg and K at Muk-Burn and % total Ca and Mg at Muk-Def in the 0-3, 3-6 and 6-10 cm depth. In the 0-3 cm depth range % total K at Muk-Def was significantly higher after burning than before burning and in the 3-6 and 6-10 cm depth range no significant difference was observed after burning. Increases in bases are due to additions in ash from burnt herbaceous and woody plant material (Raison, 1979). It was however expected that bases would significantly increase after a burn. Several workers have reported an increase in bases immediately after a fire (Viro, 1974; Woodmansee and Wallach, 1981). It is possible that some bases were lost to the atmosphere in smoke. Mackensen *et al.* (1996) reports particulate loss of bases ranging from 17-23 %; 16-31 %; 9-24 %; 17-43 % for Na, K, Ca and Mg from burnt tropical forest debri. During the month of August when burning was carried out at Muk-Burn and Muk-Def, it was very windy at

the site making it likely that some of the nutrients would be blown away in smoke. The other possibility is re-absorption of some of the nutrients by some grasses in underground plant parts; this could be a fire adaptation of some of the grass species in the savanna region.

Comparison of % microbial biomass C and N, organic C and nutrients measured was made between Muk-Burn and the other Mukuvisi Woodlands experiment sites so as to understand the long-term effect of burning in miombo woodlands. Microbial biomass C in the 0-3 cm depth range was highest at Muk-Prot compared to the other Mukuvisi experiment sites (Figure 6.3a). Microbial biomass C in this depth range at Muk-Prot was significantly higher than Muk-Burn ($p < 0.001$), Muk-Grass ($p < 0.001$) and Muk-Def ($p < 0.01$). Muk-Burn, Muk-Grass and Muk-Def had no significant difference. These results suggest that in the long term burning results in low microbial biomass C confirming results by Dumontet *et al.* (1996). Destruction of soil microbes affects nutrient cycling because they are involved in many nutrient cycling processes such as litter decomposition and N mineralization. In the 3-6 cm depth, Muk-Prot was significantly higher than Muk-Burn ($p < 0.001$) and Muk-Def ($p < 0.05$). Muk-Grass was significantly higher than Muk-Burn ($p < 0.01$). In the 6-10 cm depth range, Muk-Prot and Muk-Grass had both significantly higher ($p < 0.001$ and 0.01 respectively) microbial biomass C than Muk-Burn. In the 10-20 cm and 20-30 cm depths Muk-Prot and Muk-Grass also had significantly higher ($p < 0.001$) microbial biomass C than Muk-Burn. Microbial biomass C at Henderson sites (Figure 6.3a) was not significantly different for all depth ranges.

In the 0-3cm depth range % microbial biomass N at the Mukuvisi study sites was significantly higher at Muk-Prot compared to Muk-Burn ($p < 0.001$) and Muk-Def and Muk-Grass ($p < 0.05$). The amounts at Muk-Burn, Muk-Def and Muk-Grass were not significantly different. In the 3-6 cm depth range, there were no significant differences in microbial N for all the Mukuvisi experiment sites. However, in the 6-10 and 10-20 cm depth ranges, Muk-Prot and Muk-Grass were both significantly higher than Muk-Burn ($p < 0.001$ and 0.01 respectively). The same trend was observed for Muk-Prot and

Muk-Grass in the 20-30 cm depth ($p < 0.01$ and $p < 0.001$ respectively). At Henderson sites, there were no significant differences in microbial N. Land use practices seem to be affecting microbial N contents at Mukuvisi Woodlands experimental areas. Fire, deforestation and possibly grazing have impacted negatively on microbial biomass at Muk-Burn, Muk-Def and Muk-Grass. Dumontet *et al.* (1996) observed a decline in microbial biomass in soil surface layers 11 years after a fire, indicating that fire can have a long term-effect on microbial biomass. In the long term, burning of miombo woodland appears to have significantly lowered the levels of microorganisms in surface soils at Mukuvisi Woodlands. Burning has been noted to have detrimental effects on soil microorganisms elsewhere (Menaut *et al*, 1985; Dumontet *et al.*, 1996).

Muk-Prot (1.94 ± 0.508 %C) had the highest mean % total organic C, followed by Muk-Burn (1.86 ± 0.642 %C), Muk-Def (1.22 ± 0.100 %C) and Muk-Grass (1.14 ± 0.344 %C) with the lowest amount in the top 0-3 cm depth (Figure 6.4a). The amount of % total organic C in the 0-3 cm depth at Muk-Prot, Muk-Burn and Muk-Def was not significantly different ($p<0.05$). However, only Muk-Prot and Muk-Burn had significantly higher % total organic C ($p<0.002$) than Muk-Grass in the 0-3 cm depth range. It had been expected that Muk-Burn and Muk-Def would have lower organic C because of lower organic inputs and burning. Results possibly indicate that temperatures attained were not too high or were not sustained for a long time. Raison (1979) notes that mild fires may increase organic matter and N in upper soil layers. % total organic C in the 3-6 and 6-10 cm depth range was not significantly different for the 4 Mukuvisi Woodlands experiment sites. At Henderson experiment sites % total organic C was higher than Mukuvisi Woodlands sites ranging from 1.95 to 2.12 % (Figure 6.4a). Heavier textured soils (Henderson) are generally expected to have higher organic C than light textured soils (Mukuvisi) because organic C can interact with the clay fraction resulting in protection from decomposition. There was no statistically significant difference in % total organic C between the Henderson experiment sites at all depth ranges down to 30 cm.

The total % N in the 0-3 cm depth at Mukuvisi Woodlands was in the order Muk-Burn (0.12 ± 0.044 %), Muk-Def (0.10 ± 0.022 %), Muk-Prot (0.08 ± 0.029 %) and Muk-Grass (0.05 ± 0.013 %) (Figure 6.4b). At Muk-Burn, Muk-Def and Muk-Prot % total N were not significantly different ($p < 0.05$). However the 3 sites had significantly higher % total N than Muk-Grass (Muk-Burn ($p<0.001$), Muk-Def ($p<0.001$) and Muk-Prot ($p<0.01$)). The amount of % total N at depths 3-10 cm was not significantly different for the 4 Mukuvisi experiment sites. Henderson experimental sites were not significantly ($p<0.05$) different for all depth ranges to 30 cm. An increase in N levels was also observed after burning miombo biomass in Zambia in shifting cultivation (Stromgaard, 1992). Monitoring of N levels over a few years, without further burning revealed that the amount of N in soil reverts back to pre-burn levels (Stromgaard, 1992). At Mukuvisi Woodlands approximately 13 years of early burning has not produced a statistically significant difference in N levels in the unburnt woodland. However this is based on the assumption that before the 13 years of burning vegetation structure and soil nutrient levels were similar in the burnt and unburnt Mukuvisi Woodlands experimental areas.

At Mukuvisi sites, % total P in the 0-3 cm depth range was highest at Muk-Prot (0.06 ± 0.026 %) followed by Muk-Grass (0.03 ± 0.019 %), Muk-Burn (0.02 ± 0.011 %) and Muk-Def (0.01 ± 0.006 %) with the lowest (Figure 6.4c). Muk-Prot had significantly higher ($p< 0.01$) total P in the 0-3 cm depth than the other 3 Mukuvisi sites. Muk-Grass, Muk-Burn and Muk-Def were not significantly different ($p < 0.05$). There was no significant difference in total P in the 3-6 cm depth range. In the 6-10 cm depth range Muk-Prot had significantly higher total P than Muk-Burn ($p<0.001$) and Muk-Grass ($p<0.01$). Dumontet *et al.* (1996) reported an increase in P a year after a fire but thereafter a decline. Tsvuure (1997) observed a decline in P with increased burning frequency in miombo woodland plots burnt since 1953. At Muk-Burn, the woodland burnt, P is lower than Muk-Prot, the woodland protected from fire, indicating that P could have declined over the years. Comparison of the Henderson sites showed no significant difference ($p<0.05$) for all depth ranges to 30 cm.

The total Ca concentration in all depth ranges (Figure 6.4d) for Mukuvisi experiment sites were not significantly different. The same trend was observed for the Henderson sites. The total % Mg (Figure 6.4e) was not significantly different in the 0-3 cm depth between Muk-Burn (0.01 ± 0.003 %), Muk-Def (0.01 ± 0.003 %) and Muk-Grass (0.016 ± 0.004 %). Muk-Prot (0.02 ± 0.008 %) however had significantly higher total Mg than Muk-Burn and Muk-Def. In the depth ranges 3-6 and 6-10 cm total Mg in the 4 Mukuvisi sites were not significantly different. At Henderson sites there was no significant difference in total Mg in all the depth ranges.

In the 0-3 cm range % total K at Muk-Prot (0.35 ± 0.182) was significantly higher ($p<0.05$) than at Muk-Burn (0.19 ± 0.040 %), Muk-Def (0.10 ± 0.050 %) and Muk-Grass (0.19 ± 0.071 %) (Figure 6.4f). The amount of K in Muk-Burn, Muk-Def and Muk-Grass was not significantly different ($p<0.05$). At depths below 3 cm % total K at all the Mukuvisi sites was not significantly different ($p<0.05$). At Henderson sites there was no significant difference in total K in all the depth ranges.

Overall the bases Ca and Mg were found to be significantly higher in top-soils in the woodland area protected from fire, Muk-Prot, than the woodland burnt, Muk-Burn. Though in the case of K there were insignificant nutrient increase immediately after burning and it appears that over time the small changes are cumulative.

With the exception of N and Ca, there were higher amounts of organic C, P, Mg and K in the protected woodland (Muk-Prot) compared to the burnt woodland (Muk-Burnt) in the upper 3 cm soil layer. This probably indicates the effect of burning over the past 13 years. Burning could be slowly lowering the amount of these nutrients by making them more susceptible to leaching. Some are lost as smoke particles. It is possible that a small amount is lost through the effect of wind. Some nutrients deposited on the soil surface may be washed downslope by water during the rain season.

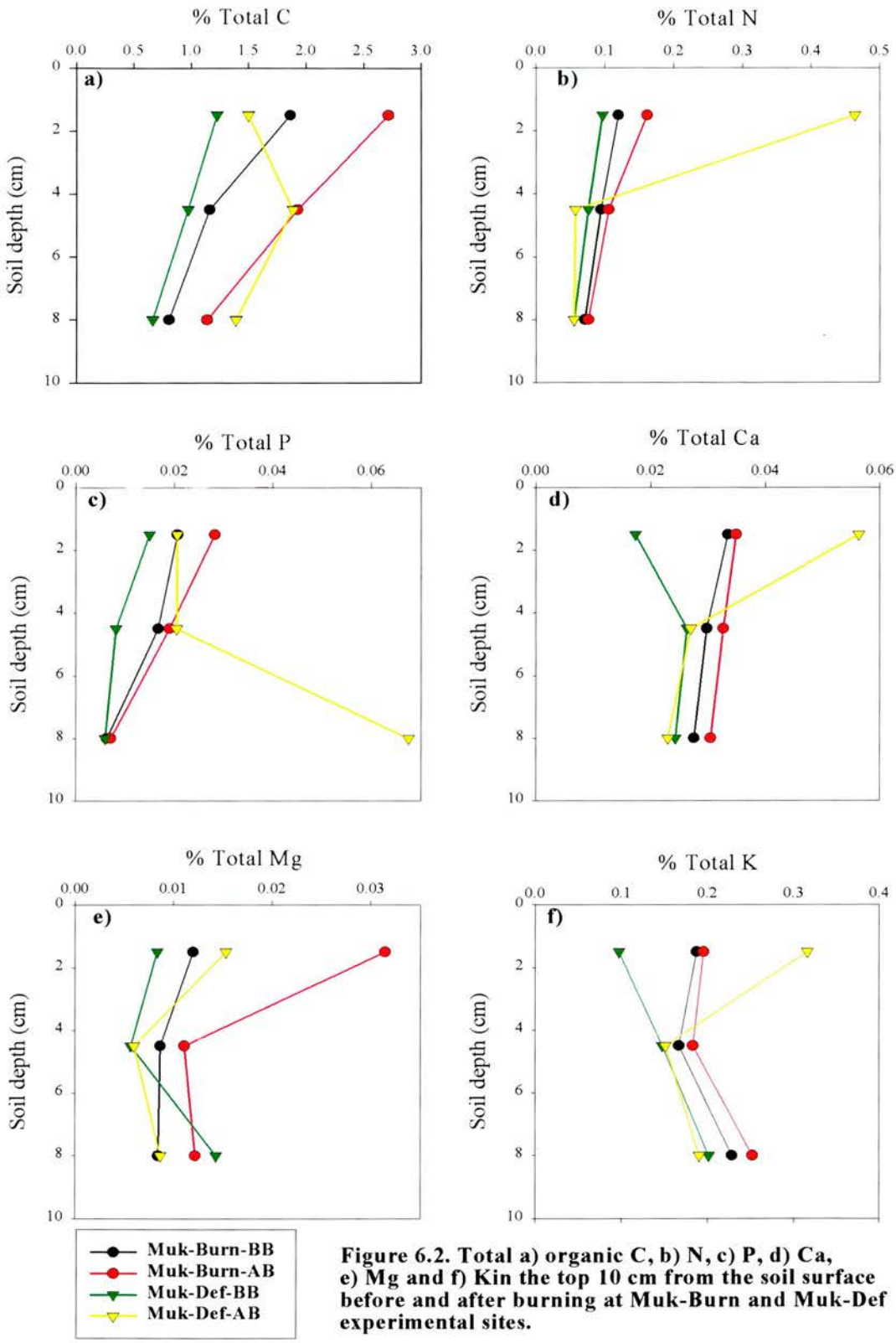


Figure 6.2. Total a) organic C, b) N, c) P, d) Ca, e) Mg and f) Kin the top 10 cm from the soil surface before and after burning at Muk-Burn and Muk-Def experimental sites.

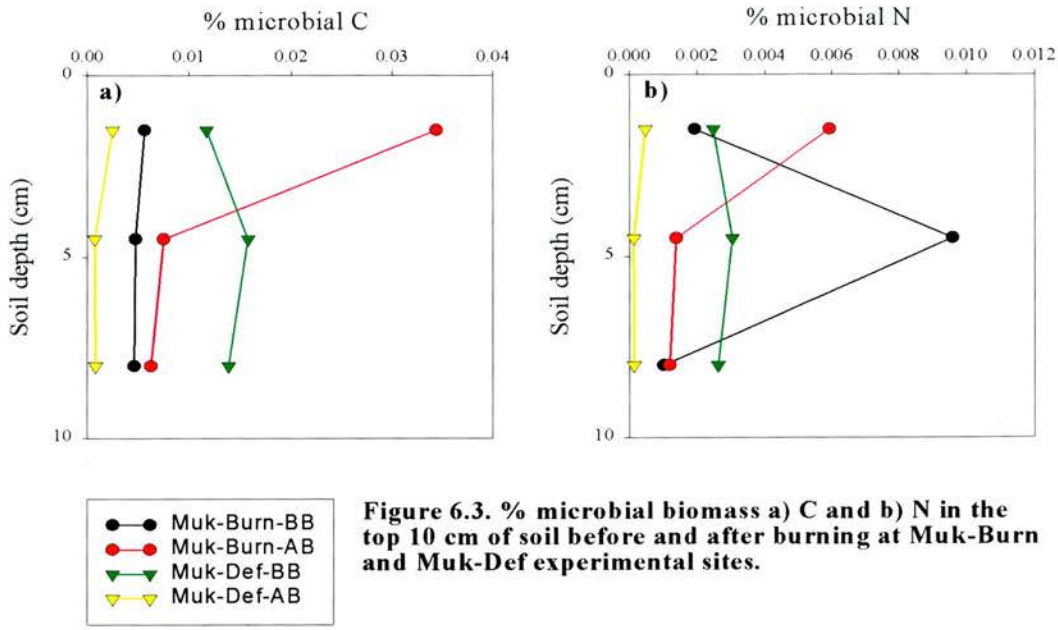


Figure 6.3. % microbial biomass a) C and b) N in the top 10 cm of soil before and after burning at Muk-Burn and Muk-Def experimental sites.

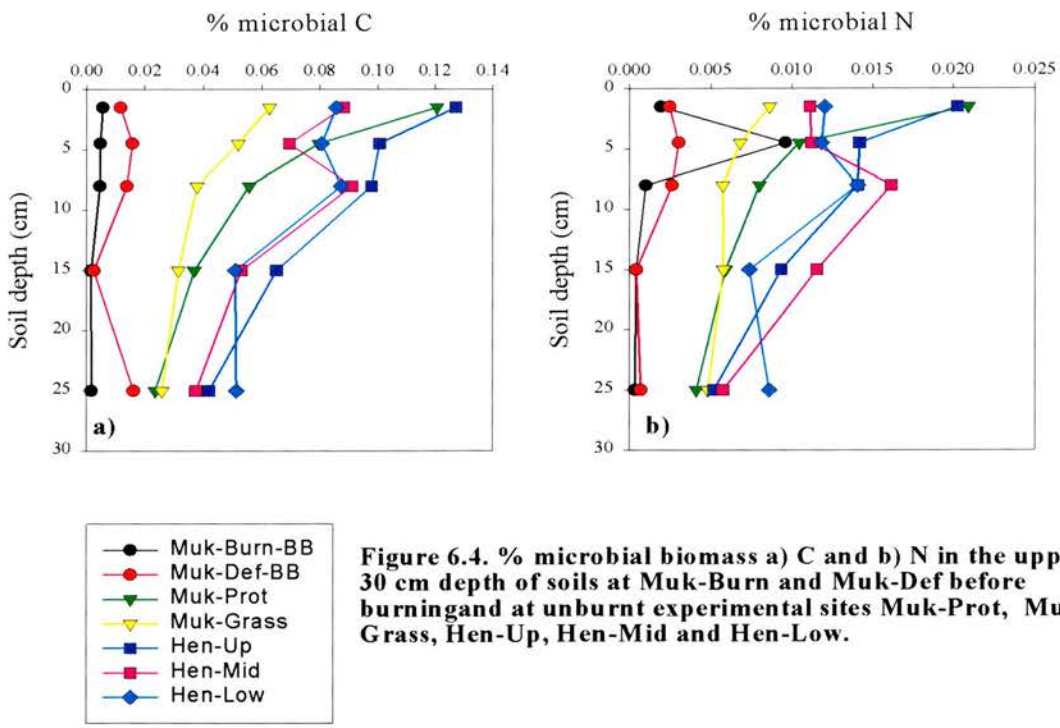


Figure 6.4. % microbial biomass a) C and b) N in the upper 30 cm depth of soils at Muk-Burn and Muk-Def before burningand at unburnt experimental sites Muk-Prot, Muk-Grass, Hen-Up, Hen-Mid and Hen-Low.

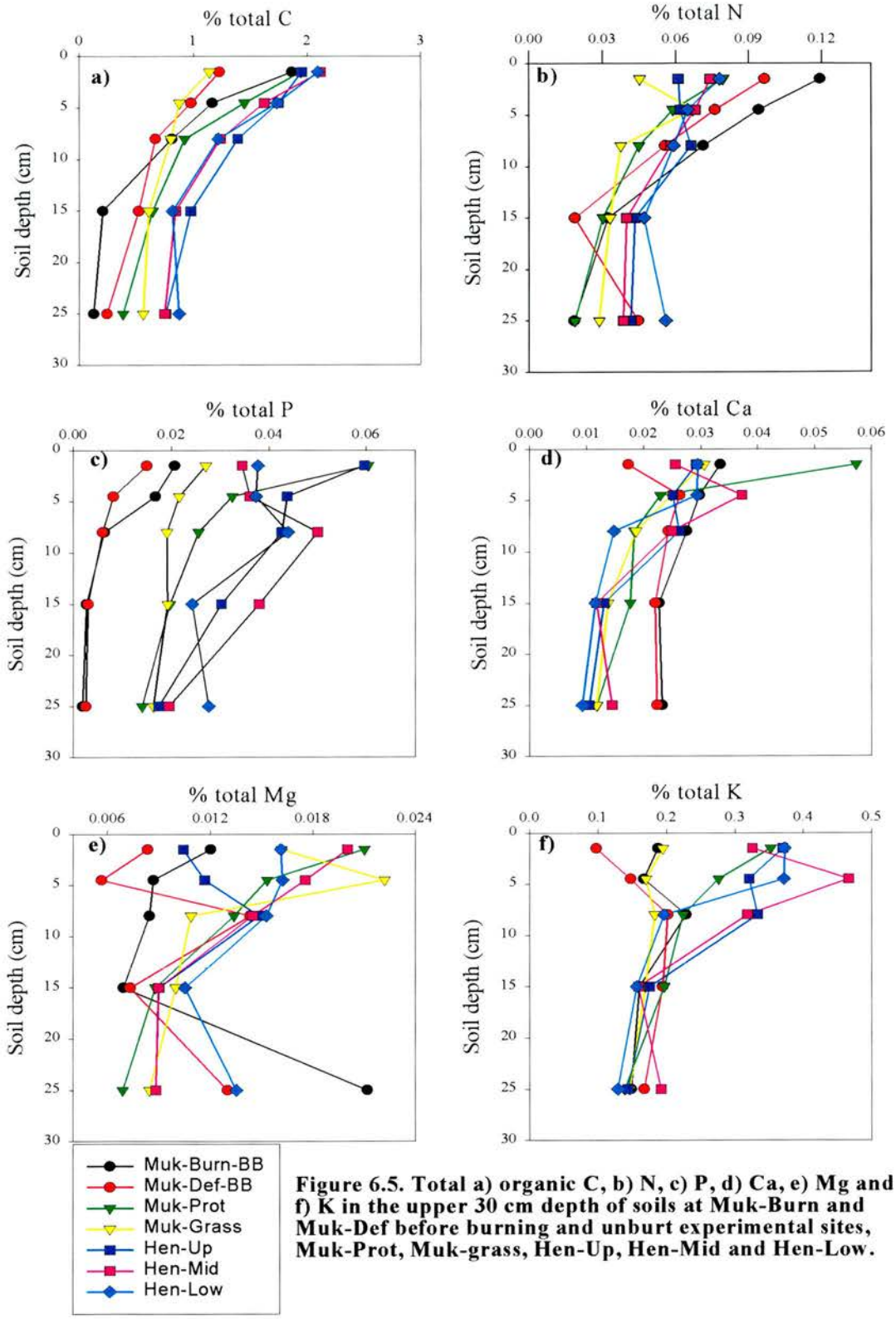


Figure 6.5. Total a) organic C, b) N, c) P, d) Ca, e) Mg and f) K in the upper 30 cm depth of soils at Muk-Burn and Muk-Def before burning and unburt experimental sites, Muk-Prot, Muk-grass, Hen-Up, Hen-Mid and Hen-Low.

Generally, there was an increase in the % total organic C and nutrients in surface soil layers immediately after burning. However this increase was not significant except in the case of total organic C and P. Compared to the unburnt woodland (Muk-Prot), the burnt woodland, Muk-Burn, had significantly lower ($p<0.05$) total P, Mg, K and organic C possibly because of a lower organic input and the destruction some litter by fire. Burning can result in nutrient enrichment of soils especially bases but in sandy soils the cations can be easily lost through leaching. Enrichment of cations (Ca, Mg, Na and K) in the surface soil is from ash deposition of plants and litter burnt (DeBano and Conrad, 1978). However, not all cations in plants end up in soil, some are lost in smoke as particulate matter. Higher enrichment of C and N to the soil could be related to low temperatures ($\approx 200^{o}C$) during a burn. Though in this study temperature was not measured, studies elsewhere show that more severe burns result in greater loss of organic matter (DeBano and Conrad, 1978). Several workers have reported an initial increase in nutrients after burning (Daubenmire, 1968a; Jordan, 1989; Stromgaard, 1992; Dumontet *et al.*, 1996) and in many cases followed by a decline over many years (Stromgaard, 1992; Dumontet *et al.*, 1996). In some cases, however, there have been reports of significant nutrient losses from surface soil layers after a burn, especially N. DeBano and Conrad (1978) reported enrichment in a chaparral ecosystem of most plant nutrients by ash material after a burn with the exception of N that had a net loss. Loss of nitrogen was attributed to high temperatures. High temperatures cause volatilization of substantial amounts of N. Christensen and Muller (1975) estimated that 21 kg/ha of N may be added to the soil surface during a savanna fire. The nutrients added are from burning vegetation. Lewis (1974) reports substantially higher nitrate and phosphate leached during the first rainfall event at a temperate burned area after a fire, but not in subsequent rains suggesting that fires make nutrients more available from litter and more prone to leaching from the litter layer. In this study there was no significant difference in N between the burnt and unburnt miombo woodland areas. These results suggest that the temperatures in top soil horizons did not rise markedly during the fire resulting in no or very small changes in N. Most of the N lost during the fire was therefore from litter and herbaceous plants.

The highest increase was always in the top 3 cm, the layer closest to the surface where burning occurs. Most of the ash from burning is therefore on the surface and is susceptible to leaching after a burn (Romanya, *et al.*, 2001). Burrowing animals to a lesser extent also mix the ash into the soil. Some of the ash may be blown away by the wind. After burning at Mukuvisi Woodland sites, there was a light drizzle (less than 5 mm). There is a possibility that the drizzle could have contributed in washing the ash into the upper soil layer. Burning resulted in an increase in amount of organic C and N compared to before burning. Matson and Vitousek, (1987) found that amounts of ammonium and nitrate increased after burning in a tropical forest and similar observations were reported by a number of workers (Jordan, 1989).

The burn at Mukuvisi is carried out during winter in July/August when some of the grass is not completely dry, resulting in irregular burning. Woodlands also have uneven distribution of fuel resulting in patchy and less intense fires (Bilbao *et al.*, 1996). Patchy fires result in patchy survival and encourage diversity patterns in fire-prone communities (Bond and van Wilgen, 1996). Though a single burn may appear irregular, it is possible that annual burning, over many years can result in a relatively uniform effect. Irregular burning results in grass and litter being partially burnt and the ash is later incorporated into soil resulting in an increase in organic C and other nutrients. Because of the patchiness, significant effects of fire on cycling of some nutrients may take many years to be noticeable. In the woodland area not burnt, that is, Muk-Prot, litter on the soil surface is incorporated slowly by animals and micro-organisms. Thus "mild or cool" fires may result in loss of N in the long term, but they may serve as a way of quickly turning back nutrients into the soil. Microbial cycling of N is enhanced after fires (Crutzen and Andreae, 1990). Ahlgren and Ahlgren (1965) found increased microbial activity after burning which could be attributed to structural vulnerability of litter after burning resulting in an increase in a readily available substrate resource. In this study fire seemed to impact negatively on microbial biomass. The problem however is the ability of the light textured Mukuvisi granitic sandy soils to hold the nutrients. It is likely that some of the cations, if not taken up by vegetation, are washed down the

profile during the rain season (Romanya *et al.*, 2001) or lost from the site by overland flow or erosion (DeBano and Conrad, 1978).

6.5. OVERVIEW

Fire resulted in significant losses of N, P, Ca, Mg, K and Na from standing herbaceous plant material in miombo woodlands. After burning, there were significant losses of N from litter. It is possible that other easily volatilized nutrients like sulphur may also have been lost (Ward, 1990). It is possible that other nutrients may have been lost from litter but surface additions in ash from burnt herbaceous plant material could have masked the change. Some of these additions end up in soils as evident from analyses of the 0-3 cm surface horizon analysed after burning.

Though the soil gains nutrients from litter and grass after a burn, overall the ecosystem loses nutrients because some of the nutrients in the litter and vegetation are lost on burning as gases and/or in smoke particles. Those added to soil may also be lost through leaching and surface wash.

Fire is however important to savanna ecosystems because it provides a rapid way of releasing nutrients into the soil and is in any case a natural feature of savanna ecosystems.

7. NUTRIENT LOSSES THROUGH LEACHING FROM MIOMBO WOODLAND TOPSOILS

7.1. INTRODUCTION

Leaching is one of the major pathways through which nutrients are lost from miombo woodlands. Leaching is the process by which material is physically removed from the soil by moving water. Soil material can be lost through leaching either in colloidal and/or solution form, including some cations exchanged from the soil surface. Nutrients lost from the woodland ecosystem may end up in streams and rivers and/or join underground aquifers. Measurement of nutrients lost from a woodland or forest ecosystem through leaching is very difficult because woodland vegetation has diverse and complex roots systems. Miombo tree roots may be more than 5 m deep with lateral roots ranging from 4 to 15 m from the main stem (Chidumayo, 1993). Leaching can remove nutrients from one part of the soil profile to another lower down the profile. It is difficult to say that the nutrients moved down lower in the profile are "lost" because the woodland vegetation may be able to pick them up because of the extensive root system. However, measurement of nutrients moved down from one part of the profile to another gives a measure of relative nutrient loss. Material can also be lost from the woodland through sub-surface lateral movement of water to streams and rivers.

The objective of this experiment was to measure the amount of nutrients, NH_4^+-N, NO_3^- N, Ca, Mg, K and Na lost from 50 cm and 100 cm depths of miombo woodland soils at Henderson Research Station experiment sites using zero-tension pan lysimeters. Lysimeters were used because they offer a good method of conducting controlled experiments under field conditions (Bergström, 1990a; Bergström and Johansson, 1991).

7.2. ASSESSMENT OF LITERATURE ON LEACHING

Nutrient leaching is a subject of interest to researchers in both developing and developed countries. In developing countries, the topic is crucial because of implications of nutrient losses for food and crop production (Nyamangara, 2001 and Kamukondiwa and Bergstrom 1994a & b). In the developed countries the concern is also focussed on environmental impacts of leaching especially nitrate (Goulding, 2000 and Goulding *et al.*, 2000). In Zimbabwe and the Southern Africa region, work on leaching is targeted at agricultural land and on identifying and measuring nutrient losses after application of organic and inorganic soil amendments. In Zimbabwe, previous research on leaching is very limited (Mills, 1976; Hagman, 1994; Kamukondiwa and Bergstrom, 1994a & b; Vogel *et al.*, 1994; Nyamangara, 2001) and there is no published research on leaching in Zimbabwean woodland and forest soils.

Leaching is an important process in the functioning of ecosystems, transferring nutrients from one part of the ecosystem to another. In the case of woodlands and forests where no fertilizer is added, nutrients lost through leaching are derived from litter decomposition, soil mineralisation processes and inputs from rainfall and throughfall. Leaching also plays an important role in soil formation and development by taking away weathering products and also transferring these products to other parts of ecosystems, or even removing them completely from the system (Jordan, 1982; Buol *et al.*, 1989). Soil solution chemistry provides information on spatial and temporal distribution of nutrients and their mobility and availability to plants (Sollins *et al.*, 1980; Litaor, 1988). Research has shown that soil solutions are an extremely important component of the chemical budget for a watershed (Sollins *et al.*, 1980; Litaor, 1988) and should therefore be included in nutrient cycling studies.

Leaching requires water and in natural ecosystems the source is rainfall. The total amount of rainfall per rainfall event, the frequency of rainfall events and soil and land characteristics like texture, slope and plant cover are some of the factors determining the amount of leaching occurring. The plant root system will also determine the amount

of nutrients lost from soils by taking up some of the nutrients and preventing loss through leaching. Although miombo woodland trees have extensive roots, most of the tree and herbaceous plant roots are confined within the top 50-60 cm depth (Rutherford, 1982; Strang, 1969).

7.2.1. Methods used for measuring leaching

There are several direct and indirect methods that are used to measure leaching and water movement in soils, among them piezometers, mole drains, neutron probes and lysimeters (Litaor, 1988). The watershed method, which uses catchments as units of measurement, has also been used to measure leaching losses (Bruinjzeel, 1991). Measurement of leaching using lysimeters is however, the most common method used in soil research. Lysimeters are devices used for measuring and collecting water moving down through the soil profile. They are used in studies of nutrient leaching (Reeder, 1986; Bergström, 1986, 1987& 1991; Kamukondiwa and Bergström, 1994a & b; Nyamangara, 2001), crop water use; pesticide translocation (Bergström, 1990c; Watt and Hall, 1996) and colloid transport (Thompson and Scharf, 1994).

There are different types of lysimeters used in leaching studies and these can be grouped into zero tension or free draining and tension or suction lysimeters. Zero tension lysimeters collect soil water with a collector or pan as it percolates down the soil profile via gravity (Litaor, 1988; Jemison and Fox, 1992). They are therefore mainly used to collect water in soils under saturated gravity flow. Tension or suction lysimeters have a suction device attached to the bottom of the lysimeters allowing water to be drawn at a certain tension through a porous ceramic cup. Zero tension lysimeters are easy and cheap to install and maintain. However, their main shortcoming is the alteration of hydraulic conductivity in the soil above and below the lysimeter due to a water saturated zone which can occur in the profile because of resistance formed by the surface tension between the soil-air boundary (Reeder, 1986). Tension lysimeters however overcome this problem by use of a suction device but they are difficult to install, expensive and have high maintenance costs. They are therefore used mainly in studies using disturbed soils. Despite the limitations, over the long-term both systems

are adequate for leaching studies (Bergström, 1990a) and other workers (Russel and Ewel, 1985) have demonstrated that zero-tension lysimeters provide satisfactory water flux estimates. The difference in amount of leachate collected between the zero tension and the tension lysimeter solutions is higher in surface soils and decreases with increasing depth (Cozzarelli *et al.*, 1987; Joslin *et al.*, 1987). These results suggest that preferential flow is most important in the surface layers where the macropore density, related to biological activity is highest and along cracks. Preferential flow results in by-passing of the soil matrix and preferential leaching along the preferred path. It can result in high or very low soil water solution being collected in lysimeters. High amounts of water are collected when lysimeters are located on the preferred flow paths, whereas low amounts are collected when lysimeters are located in an area by-passed by the soil water. It has been observed that water collected from preferred flow paths have lower cation concentrations than water flowing through the soil matrix (Nortcliff and Thornes, 1989). A relatively large pan lysimeter can minimize errors due to preferential flow because it collects soil water over a large surface area (Barbee and Brown, 1986; Radulovich and Sollins, 1987). Barbee and Brown (1986) found that 30cm x 30cm pan lysimeters collected more water than porous cups in well structured soils because rapidly moving leaching water by-passed the porous cups. Occassionally, zero-tension lysimeters can record volumes of water in excess of incident rainfall because of collection of channelled subsurface flow (Russell and Ewel, 1985). Other workers, however, point out that some of these problems can be eliminated by the use of the watershed method where water draining from a catchment area is measured in a river or stream (Bruinjzeel, 1991). River or stream water integrates various flow types from an area. The method however has some disadvantages. Variation in soil and vegetation types makes it difficult to assign losses to the different soil and vegetation areas in the catchment. In many areas, not all water from the catchment flows into the river draining from the area resulting in some of the water going unrecorded. Some water may be lost through deep seepage through rock fissures and alluvial deposits resulting in under-estimation of nutrients lost in drainage water.

The water-collecting part of lysimeters is either embedded in soil columns or attached a the bottom of the column. Columns can either be made of disturbed or undisturbed soil. Disturbed lysimeters are made by re-packing soil in a casing which may be made of galvanised or stainless steel (Cassel *et al.*, 1974; Brown *et al.*, 1985; Reeder, 1986), plastic (Bergstrom, 1992; Thompson and Scharf, 1994) or glass fibre (Belford, 1979). Disturbed lysimeters are easier to make but soil disturbance results in alteration of soil properties such as soil structure and hydraulic conductivity. Undisturbed soil columns are collected from the field as large soil monoliths enclosed in a casing. This process is time consuming, expensive and transportation of the columns to lysimeter stations is difficult (Bergstrom, 1990). They are also difficult to collect in woodlands and forests where there are many large roots. Enclosed lysimeters are important in monitoring and measuring leaching and dissipation of applied chemicals, such as fertilizers and pesticides, over a fixed area. The main disadvantages of enclosed systems is that the soil inside the lysimeter is separated from the surrounding soil and effects of lateral flow are excluded. There is also a tendency for side wall flow, which however can be minimized by painting lysimeter walls to provide a rough surface. Cost and practicability limit the size of the undisturbed soil column that can be collected. Zero tension lysimeters can however, be easily installed in the field in a soil pit (Watts and Hall, 1996) by removing soil from a small section of the pit wall for placement of the water collection device. After embedding the lysimeter, soil is carefully re-packed in and around the lysimeter. In this case, no casing is necessary, thus mimicking field conditions as far as possible. For the present research, this procedure was considered to be the most appropriate.

7.3. MATERIALS AND METHODS

Leaching measurements were conducted only at the Henderson Research Station experimental sites. It was not possible to carry out a similar experiment at Mukuvisi Woodlands because maintaining soil pits for an extended period was considered to be dangerous to the wild animals kept at this site.

Three replicate soils pits, 1.5 m x 1.5 m x 1.5 m, were dug in each Henderson experiment area, making a total of 9 pits at the study site. The dimensions of the pits used enabled easy installation of the lysimeters. Auger observations were used to identify representative sites for the soil pits. In each pit, two pan lysimeters were placed at 50 and 100 cm depth (Figure 7.1). These sampling depths were used because most of the roots in miombo woodlands are in the 50-60 cm depth range and the sampling depths selected allowed one to determine the amount of nutrients moved from the soil horizons with many roots.

The lysimeters were installed by digging a tunnel into the side-wall and placing the pan lysimeters inside the tunnel a minimum of 30 cm from the wall surface (Radulovich and Sollins, 1987). The pan or plastic water collecting device had a base area of 30 cm x 32 cm with a height of 5 cm. The plastic collector was made such that collected water flowed easily to the outlet. A plastic tubing was connected to the outlet of each pan to allow the leachate to flow into a 2L water collecting bottle (Figure 7.1).

After about a month the 2 L plastic water collecting bottles were replaced by 5 L bottles. A 5 mm plastic mesh was fixed in the lysimeter pan water outlet after plugging the outlet with porous glass wool (Radulovich and Sollins, 1987). A thin layer of river sand was placed at the base of the lysimeter. Soil removed was carefully repacked inside and around the pan lysimeter ensuring that the lysimeter remained level. The lysimeter at 50 cm and 100 cm depths were located on opposite sides across the slope. In stony soils where sometimes this was not possible, it was ensured that the lysimeter at 100 cm was not directly below that at 50 cm depth. The distance between the vertical lines through the centre of lysimeters was at least 50 cm. Lysimeters were installed in September, just before the beginning of the 1999/2000 rain season. They were left for about a year before taking measurements to allow the soil to settle and the sampler surface to equilibrate with the surrounding soil (Litaor, 1988). Thus leaching sampling and measurements were taken in the 2000/2001 rain season.

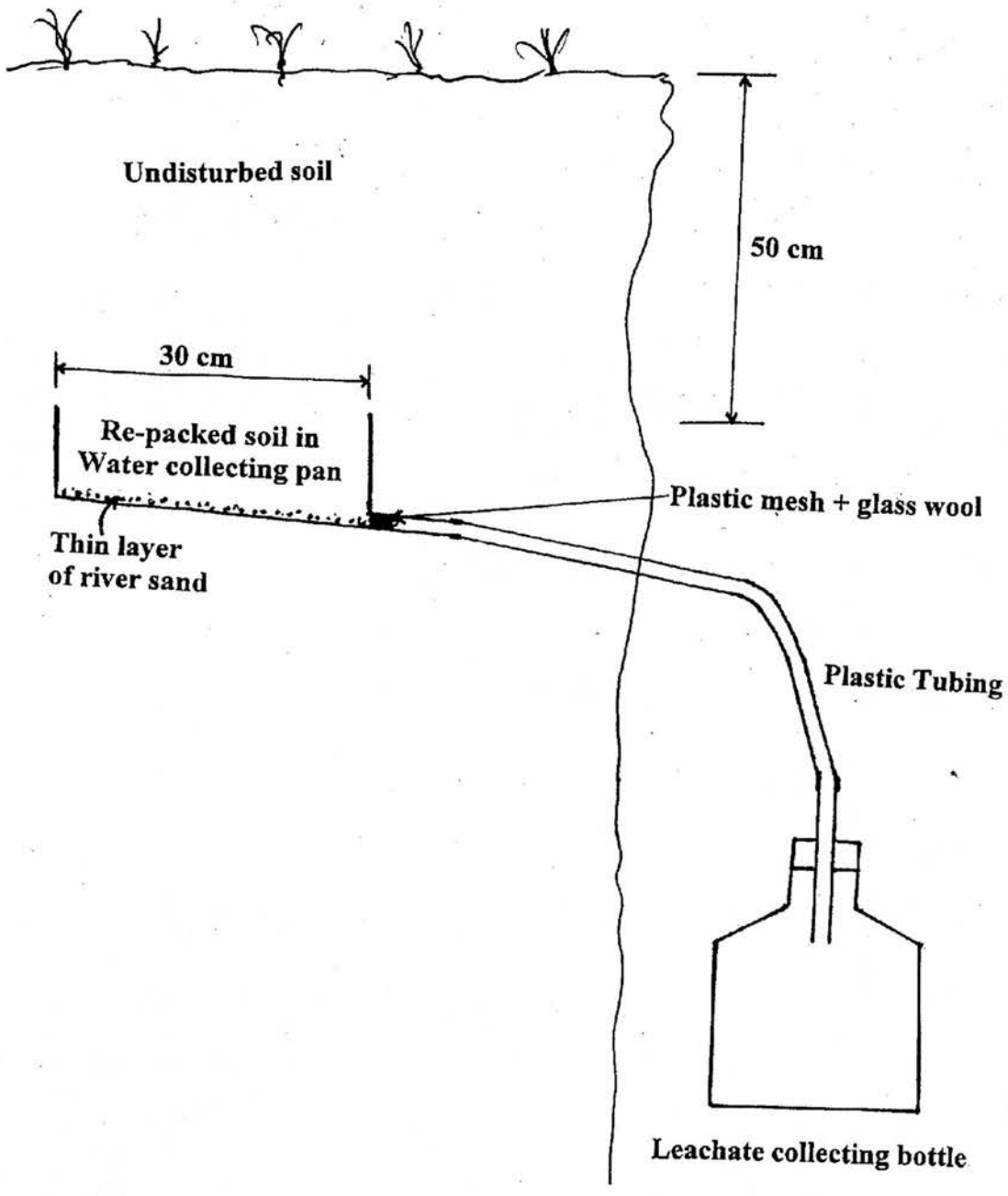


Figure 7.1. A diagram of a pan lysimeter used to measure leaching at the Henderson Research Station experimental areas (Hen-Up, Hen-Mid and Hen-Low). Leachate samples were collected from 50cm and 100 cm depths. The pan was inserted by digging a small tunnel into the soil pit side wall and placing the pan inside before carefullly re-packing the soil to close the tunnel.

Water was collected after each rainfall event, the volume recorded and a sample taken for laboratory analysis. Samples were filtered on arrival at the laboratory and where analysis could not be done immediately on the same day, they were stored in a freezer. A composite volume weighted sample for each lysimeter for each month was analysed for pH, NH_4^+-N , NO_3^-N, Ca, Mg, K and Na using the methods described in section 3.2.4.

7.4. RESULTS AND DISCUSSION

7.4.1. Leachate volumes

The mean total annual rainfall received at Henderson research station in the 2000/2001 rain season was 855 mm (Table 7.1). However the amount of rainfall reaching the soil surface after interception by vegetation, that is, throughfall, was different for the 3 experimental areas (Table 7.1). Almost all the rainfall reaching the soil surface is throughfall with the contribution from stem flow being negligible (Table 4.3, Chapter 4.). Hen-Up received 807 mm, Hen-Mid 730 mm and Hen-Low 745 mm of throughfall. The range of the amount of leachate expressed as a percent of rainfall, was 8.8 to 22.6 %. This was as expected lower than results from a Zimbabwean granite derived sandy clay loam soil where leachate volumes ranged between 34 and 39 % of rainfall (Nyamangara, 2001).

It is likely that a significant proportion of rainfall reaching the soil surface was lost as overland flow especially from Hen-Up topographic location. Other workers however report that in structured soils preferential flow is common and preferentially moving solutes may by-pass the water pan collector thereby resulting in underestimation of the amount of leachate (Radulovich and Sollins, 1987; Jemison and Fox, 1992). It was however not possible to confirm these possible water losses during the experiment.

Table 7.1. Mean total leachate (mm/year) collected from 50 and 100 cm depths at Hen-Up, Hen-Mid and Hen-Low during the 2000/2001 rain season. Leachate was expressed as a percentage using total annual rainfall received at Henderson Research Station experiment sites during the same season. (SE- Standard error of the means).

Site	Lysimeter depth (cm)	Rainfall (mm/year)	Throughfall (mm/year)	Mean total Leachate (mm/year) (± SE)	% Leachate
Hen-Up	50	855	807	122.5 ± 18.5	14.3
	100			74.9 ± 13.6	8.8
Hen-	50	855	730	173.3 ± 18.2	20.3
Mid	100			118.3 ± 15.2	13.8
Hen-	50	855	745	193.7 ± 24.3	22.6
Low	100			131.4 ± 17.8	15.4

Leachate volumes, as expected, increased with an increase in the amount of rainfall received at Henderson Research Station (Figure 7.2). The highest amount of leachate at all the experiment sites was in February, 2002. During this month the experiment sites received the highest amount of rainfall (Figure 7.2). Though throughfall was generally higher at Hen-Up, this experiment site had the lowest leachate (122.5 and 74.9 mm at 50 cm and 100cm depth respectively) collected. This area occupies the upper slope position on the catena and has a slope range of about 5 to 8 % compared to 2 to 3 % and 1 to 2 % at Hen-Mid and Hen-Low experiment areas respectively. It is likely that more water was lost through overland flow and less infiltrated into the soil in the upper slope site resulting in accumulation of material downslope. Hen-Low had the highest leachate volumes with cumulative volumes for the 2000/2001 rain season of 193.7 and 131.4 L/m^2 from lysimeters at 50 cm and 100 cm respectively. Cumulative leachate volumes for Hen-Mid was 173.3 and 118.3 L/m^2 for lysimeters at 50 cm and 100 cm depth.

At all sites, leachate collected from 50 cm depth was higher than that at 100 cm. In topsoil preferential flow is known to be dominant (Radulovich and Sollins, 1987; Jemison and Fox, 1992). Preferential flow is movement of water along channels rather through the soil matrix and this can result in more water being collected. Many workers report that this is prevalent in forest soils (Smetten and Trudgill, 1983; Russel and Ewel, 1985 and Radulovich and Sollins, 1987). The amount of water moving down a soil profile depends on properties such as, slope, soil texture, soil structure which affect the hydraulic properties of soils. The 3 experiment sites have different slopes and this resulted in significant overland flow from Hen-Up, that is, the upper slope site to Hen-Mid and Hen-Low, the middle and lower slope sites. More gentle slopes are likely to increase the residence time of water from rainfall increasing the possibility of infiltrating into the soil. Some of the water drained into a stream through overland flow and sub-surface lateral flow from the lower part of Hen-Low site. Soil texture of the soils in the 3 experimental sites was similar (Appendix 3). However, soil structure was different, with Hen-Up and Hen-Mid soils having weak to moderately developed subangular blocky structure. Soils in Hen-Low have strongly developed subangular blocky structure and several cracks were evident. This suggests a greater fine fraction component which is likely, given the accumulation zone characteristics.

Evapotranspiration lowers the amount of leachate measured because vegetation take up some of the water from the soil. There is also direct water loss from the soil surface due to evaporation.

7.4.2. Nutrient concentrations and loads in leachates

The concentration of nutrients in eluvial solution generally increased from the beginning of the rain season decreasing at the end of the season (Figure 7.3). However, nutrient concentrations varied from month to month over the rain season. Nutrient concentrations in leachate collected at 100 cm depth were generally lower than those collected at 50 cm depth. The lowering of nutrient concentration could be attributed to uptake by vegetation and also translocation by through-flow or lateral flow within the soil profile.

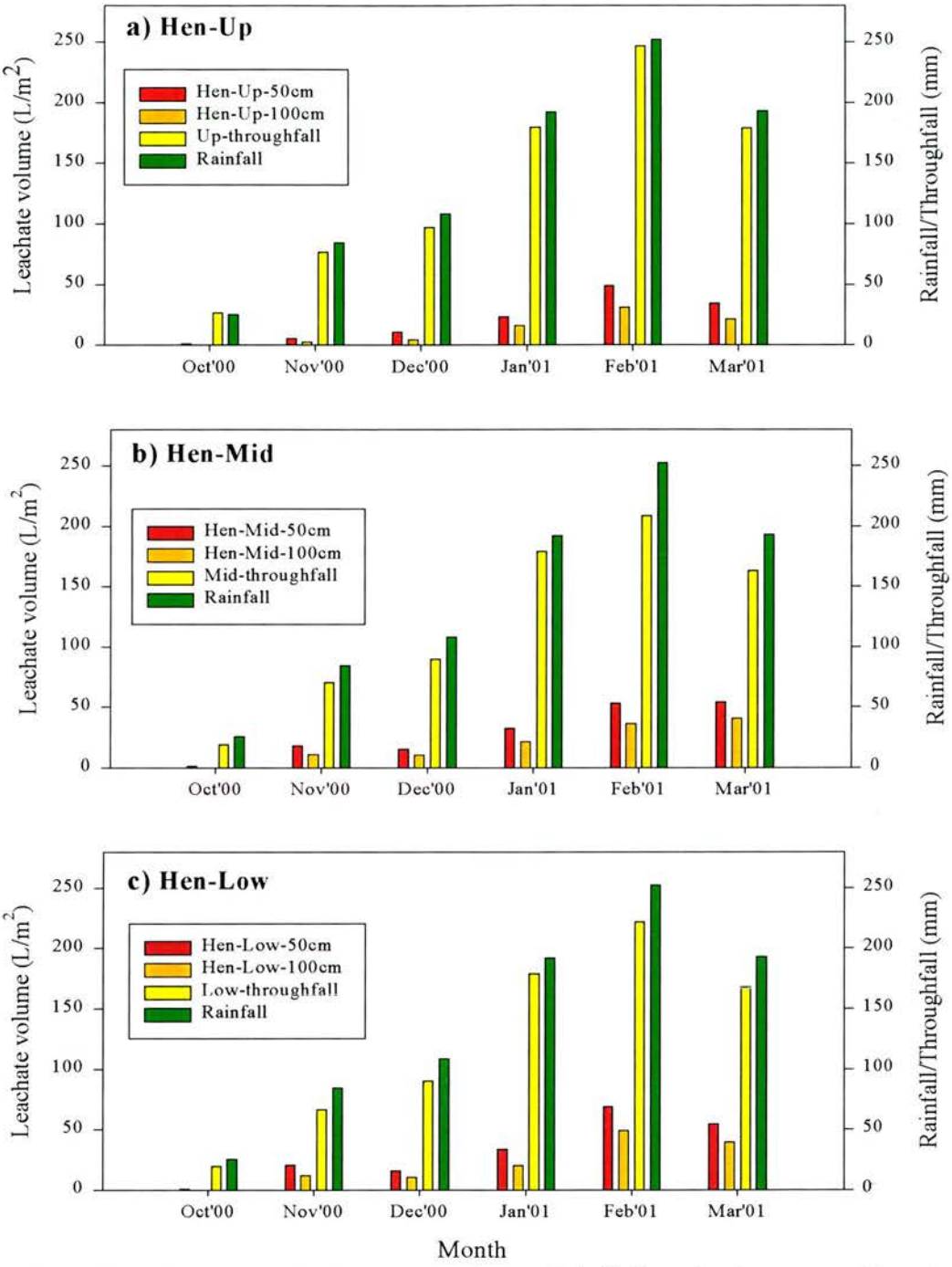


Figure 7.2. Mean monthly leachate volumes (L/m^2) from lysimeters at 50 and 100 cm depth; throughfall (mm) and rainfall (mm) received at Henderson Research Station experimental areas, a) Hen-Up, b) Hen-Mid and c) Hen-Low, during the 2000/2001 rain season

The amount of mineral N, that is, NH_4^+-N and NO_3^--N, in leachates increased during the middle of the rain season corresponding to the period when there was relatively higher N mineralisation (see chapter 8.). The amount of NO_3^--N (111 to 358 mg/m^2/year) in leachate was found to be generally higher than NH_4^+-N (39 to 142 mg/m^2/year). NO_3^--N is more susceptible to leaching compared to NH_4^+-N which tends to be more tightly held on clay exchange sites. The total annual amount of NO_3^- -N in leachate from miombo woodland soils were lower than results from an unfertilized field where leachate collected from a sandy clay loam soil at 100 cm depth had NO_3^- -N loads of 1180 and 1890 mg/m^2/year (Nyamangara, 2001). Nutrients lost through leaching from natural woodlands is lower than from cultivated fields indicating that the natural ecosystem probably conserves nutrients from leaching loss most likely through uptake.

Compared to the inputs into the woodlands it is evident that the woodland system does not have a net loss. The bases measured in leachate were Ca, Mg, K and Na. The cation with the highest concentration in leachate was K (Figure 7.3). The relative abundance of cations in leachates in decreasing order was K> Ca> Na> Mg.

The nutrient loads in leachate are determined by the concentration of the cation and the leachate volume. The total amount of nutrients leached was higher for lysimeters at 50 cm depth than at 100 cm depth (Figure 7.4). The mean total nutrient loads in leachates were evaluated using analysis of variance. The significantly different pairs of means were identified using Fisher's Least Significant Difference (LSD). Statistical analysis showed that there was a significant difference ($p > 0.01$) in NH_4^+-N and NO_3^--N total cumulative loads in leachate from 50 cm and 100 cm depth at each of the experiment areas. Amounts were always higher in leachate from 50 cm than from 100 cm depth (Figure 7.4). Across the 3 areas leachate loads of NH_4^+-N and NO_3^--N from 50 cm depth was significantly different ($p > 0.01$), with Hen-Low having the highest amount of both NH_4^+-N and NO_3^--N (140.4 and 357.6 mg/m^2/year respectively), followed by Hen-Mid (135.0 and 294.2 mg/m^2/year respectively) and Hen-Up had the lowest (90.7 & 214.7 mg/m^2/year).

Table 7.2. Nutrient additions in rainfall, net throughfall (nutrients derived from the canopy) and stem flow and loss through leaching at 100 cm depth at Henderson experiment sites during the 2000/2001 rain season.

Site	Nutrient	Rainfall (kg/ha/year)	Net Throughfall (kg/ha/year)	Stem flow (kg/ha/year)	Total leached nutrient at 100 cm depth (kg/ha/year)
Hen-Up	NH_4^+-N	2.92	0.08	0.04	0.39
	NO_3^- -N	2.79	0.02	0.03	1.11
	Ca	0.93	3.39	0.06	0.82
	Mg	0.17	0.28	0.02	0.32
	K	1.19	4.21	0.14	1.24
	Na	0.21	0.52	0.07	0.28
Hen-Mid	NH_4^+-N	2.92	0.31	0.05	0.69
	NO_3^- -N	2.79	0.27	0.03	1.33
	Ca	0.93	3.23	0.07	1.28
	Mg	0.17	0.32	0.02	0.43
	K	1.19	4.04	0.16	2.47
	Na	0.21	0.58	0.08	0.37
Hen-Low	NH_4^+-N	2.92	0.71	0.04	0.83
	NO_3^- -N	2.79	0.89	0.04	2.30
	Ca	0.93	3.66	0.08	1.49
	Mg	0.17	0.36	0.02	0.52
	K	1.19	4.34	0.25	2.52
	Na	0.21	0.71	0.09	0.54

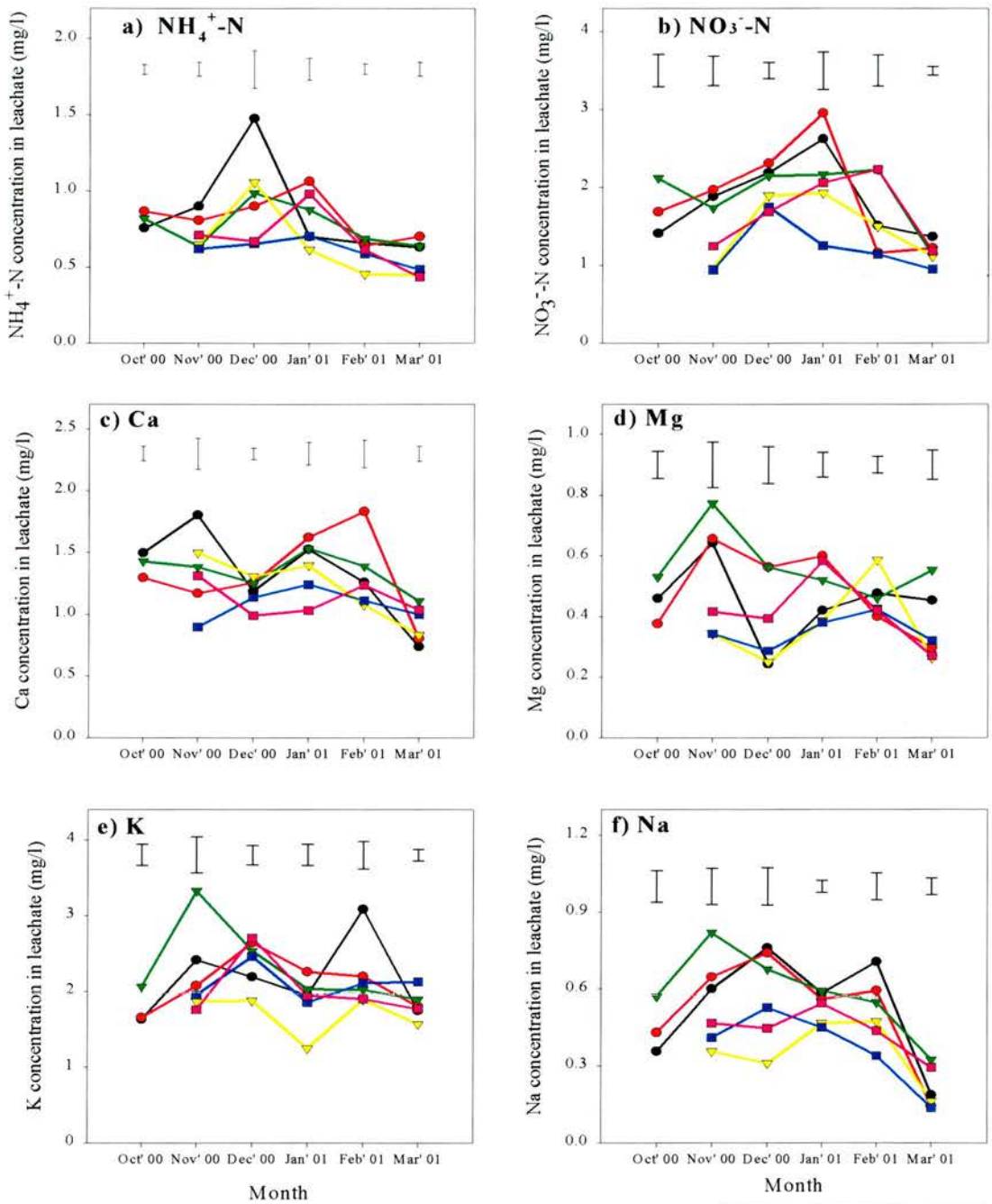


Figure 7.3 Concentration of a) NH_4^+-N, b) NO_3^--N, c) Ca, d) Mg, e) K and f) Na in leachates collected at 50 cm and 100 cm depths at Hen-Up, Hen-Mid and Hen-Low experiment areas throughout the 2000/2001 rain season. Leachate at 100 cm was only available a month after the onset of the rain season from November (Bars represent standard errors of means and n = 6).

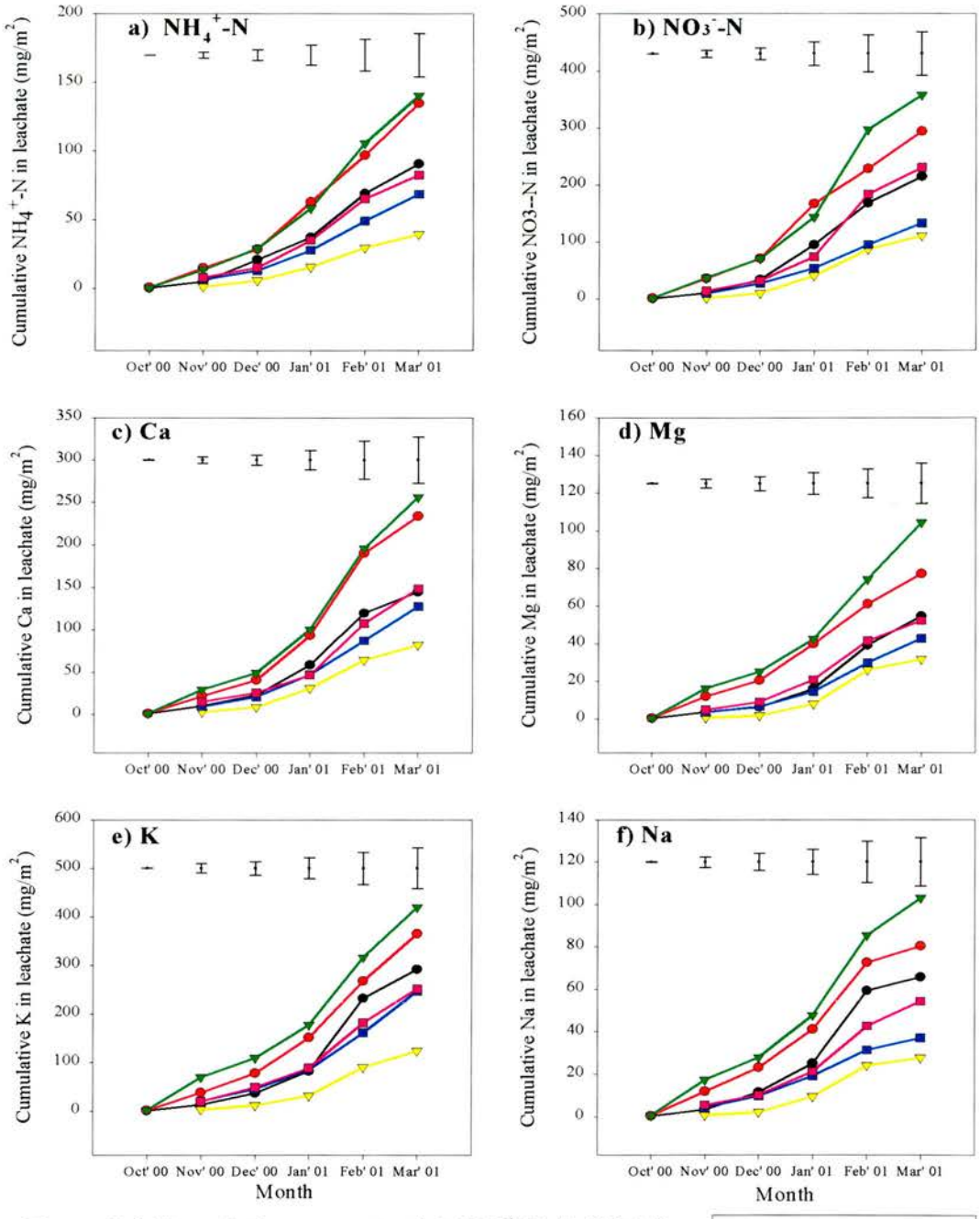


Figure 7.4. Cumulative amounts of a) NH_4^+-N, b) NO_3^--N, c) Ca, d) Mg, e) K and f) Na (mg/m^2) in leachates collected at 50 cm and 100 cm depths at Hen-Up, Hen-Mid and Hen-Low experimental areas during the 2000/2001 rain season. The cumulative amounts of nutrients leached to 50 cm depth were higher than at 100 cm depth (bars represent standard errors of means, n = 6).

Leaching of NO_3^- -N would be expected to be greater than NH_4^+-N because of the greater mobility of nitrate-N (Kamukondiwa and Bergström, 1994b; Ulén, 1999). All NO_3^--N leachate loads from 100 cm depth from all the experiment sites were significantly different ($p > 0.01$) with the exception of the pair Hen-Up (100cm) and Hen-Mid (100cm). However, for NH_4^+-N from the same depth, there was no significant difference across the experiment sites. The total amount of NH_4^+-N and NO_3^--N leached from the soil to 100 cm depth was higher than total additions in throughfall and stemfall combined (Table 7.2). The most likely additional sources of the leached mineral N is the decomposing litter on the soil surface and the mineralisation of organic N in the soils.

The total cumulative Ca and Mg amounts in leachates from 50 cm depth were not significantly higher ($p > 0.01$) than leachates collected from 100 cm depth at each site (Figure 7.4). Cumulative leachate loads of Ca and Mg from the 3 sites at 50 cm depth were not significantly different. The same trend was observed for leachate from 100 cm depth. Amounts equivalent to between 23 and 40 % of Ca added to the soils in throughfall and stem flow were leached to 100 cm depth (Table 7.2). Amounts of Mg higher than the total added in throughfall and stem flow was however leached from the soil. Some of the Mg leached is likely to be from the soil and the decomposing litter.

The total cumulative amounts of K and Na in leachates from 50 cm were all significantly higher ($p > 0.01$) than in leachate from 100 cm at each site with the exception of K in leachates collected at Hen-Mid. Comparison of leachates from 50 cm depth from the 3 sites showed that only the pair Hen-Up and Hen-Low were significantly different ($p > 0.01$) in Na loads. However, K and Na in leachates from 100 cm depth from the 3 sites were not significantly different. The cations K and Na had the highest amounts leached from the soil (Table 7.2) because of their greater mobility compared to Ca and Mg.

Bate and du Preez (1981) found negligible nutrient leaching losses above the water table in a savanna woodland in South Africa. In this study the amounts of NH_4^+-N, NO_3^--N and

Mg in leachate from 100 cm depth were higher than the sum total of additions to the woodland in throughfall and stem flow. Likens *et al.*, (1977) report that most ecosystems have lower atmospheric nutrient inputs compared to leaching losses. This probably explains why miombo tree species need to conserve the nutrient N by withdrawing nutrients from senescing leaves. The amounts of Ca, K and Na in leachate were however lower than the sum total in throughfall and stem flow. K, which was the highest nutrient in rainfall, throughfall and stem flow (Chapter 4) was also found to be highest in leachate with Na and Mg having the lowest amounts.

7.5. OVERVIEW

Potassium (K) and NO_3^--N were the nutrients in leachate with the highest concentrations. Nutrients added to soils are moved down the profile with moving water. Compared to the amounts in throughfall and stem flow, it was evident that the amounts of nutrients Ca, K and Na were lower in leachate samples collected at 100 cm depth showing that some nutrients may be retained in the top-soils. However a greater amount of the nutrients NH_4^+-N, NO_3^--N and Mg were leached to 100cm depth compared to the amounts added in rainfall, throughfall and stem flow. The source of nutrients in leachate could be from throughfall, stem flow, decomposition and mineralisation of litter and organic matter in the soil. It is possible that some nutrients were also lost through erosion and overland flow (Heilman and Norby, 1998) or oblique percolation through the profile, but these pathways were not measured in this study. However, losses of N through nitrous oxide emissions were measured at both Mukuvisi Woodlands and Henderson Research Station experimental areas and the results are discussed in chapter 8.

8. NITROUS OXIDE EMISSIONS FROM MIOMBO WOODLANDS

8.1. INTRODUCTION

Gaseous emission is one pathway through which the nutrient nitrogen may be lost from miombo woodland ecosystems. N is studied here as a surrogate for measurements of all the possible gas fluxes from the soil because it is a critical element in nutrient dynamics. Gaseous forms of nitrogen are lost by the processes, nitrification and denitrification. Nitrogen is lost from soils as either nitric oxide (NO), nitrous oxide (N_2O) and/or nitrogen gas (N_2). Besides being a loss of N, N gases emitted cause environmental problems especially N_2O which acts as a greenhouse gas and NO which catalyses the formation of ozone in the troposphere and the destruction of ozone in the stratosphere (Bouwman, 1990a). N_2O is stable in the troposphere where it absorbs infrared radiation and functions as a greenhouse gas. It reacts with ultraviolet radiation in the stratosphere resulting in the formation of NO that reacts with ozone causing its depletion. Unlike N_2O, NO is very reactive in the troposphere (Bouwman, 1990a; Vitousek and Matson, 1992). It causes acid rain and photochemical production of ozone during oxidation of hydrocarbons and carbon monoxide (Smith *et al.*, 1997). Elevated levels of ozone in the troposphere are highly damaging pollutants, contributing to the greenhouse effect (Vitousek and Matson, 1992).

Compared to CO_2 emissions, the amounts of N_2O emissions are far much lower but it has a global warming potential of 320 times more than CO_2 (IPCC, 2001). In the past two centuries atmospheric N_2O has increased by about 13 percent necessitating the need for identifying sources of this gas. There is therefore a need to measure N gas emissions because they are an important component in N cycling and N circulation is a critical component of miombo woodland geochemical cycling.

N_2 emission is difficult to measure because background levels in the atmosphere are very high. Researchers overcome this problem by inhibiting further reduction of N_2O to N_2 gas using acetylene (Bouwman, 1990b) and then analyzing N_2O. Nitrogen is also

lost from tropical ecosystems as NO (Johansson *et al.*, 1988; Johansson and Sanhueza, 1988) and can be measured using a chemiluminescent NO/NO_2 analyser (Johansson *et al.*, 1988; Johansson and Sanhueza, 1988; Mosier *et al.*, 1998).

Soils in the tropics are believed to be important sources of N_2O and NO emissions. Measurements in moist tropical forests in South America have shown that tropical ecosystems contribute comparable or greater amounts to the atmosphere than temperate forests (Keller, *et al.*, 1986; Livingston *et al.*, 1988; Matson and Vitousek, 1990; Hall and Matson, 1999). Measurement of N_2O and NO from seasonally dry tropical woodlands and forests is therefore important because it improves our estimates of these systems as sources and our understanding of N nutrient dynamics and turnover. Little is known about the fluxes of N_2O from miombo woodlands. The limited work done so far in Zimbabwe has focussed on NO fluxes from miombo woodlands (Meixner *et al.*, 1997). In the present study NO could not be measured because of lack of adequate equipment. It was decided to measure only N_2O to give an indication of gaseous N loss from miombo woodlands.

The objective of this experiment was, therefore, to measure the loss of nitrogen as N_2O from miombo woodlands and to determine the effect of soil moisture and temperature on these fluxes.

8.2. NITROUS OXIDE EMISSIONS FROM SOILS

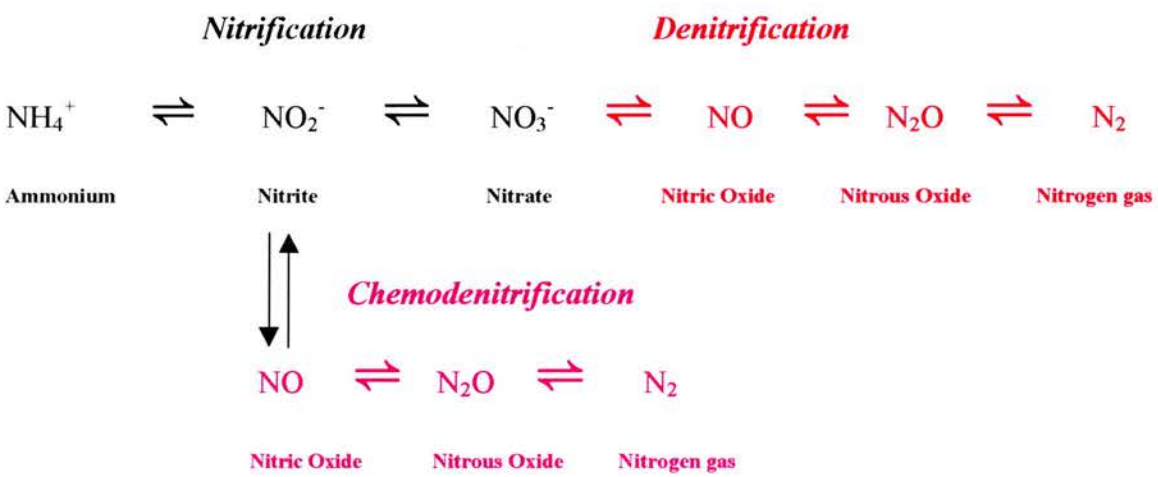
8.2.1. Introduction

Nitrogen can be lost from terrestrial ecosystems as nitrous oxide (N_2O) emissions. Nitrous oxide is a greenhouse gas emitted naturally by biological processes from soil and water bodies (Bouwman, 1990b; Riley and Vitousek, 1995) as a consequence of N turnover. The amount emitted can be enhanced by land use change, agricultural, industrial activities, combustion of solid wastes and fossil fuels. Measurement of N_2O is very important because of its impact on the environment. It has a lifetime of between 100 to 200 years in the atmosphere and hence changes in its concentration has long-

term effects (Bouwman, 1990b; Liu and Reiners, 1999). Production of N_2O from terrestrial ecosystems occurs continuously in small amounts and this is the main source of N_2O in the atmosphere (Freney *et al.*, 1979). N losses from terrestrial ecosystems like forests and woodlands, therefore need to be measured.

8.2.2. Processes involved in the formation of N_2O

Production of N_2O is related to N transformations occurring in the soil, with high N_2O emissions being associated with high transformations rates of N (Riley and Vitousek, 1995). Nitrification and denitrification are the sources of N_2O and these processes can occur simultaneously in soils (Abbasi and Adams, 2000 a & b). Nitrification occurs in well aerated soils and involves the oxidation of NH_4^+ to NO_2^- and NO_3^- (Bouwman, 1990b) as shown by the equations below.



N_2O can also be produced by nitrification and under aerobic conditions this can be the dominant N_2O producing process (Bremner and Blackmer, 1978; Mosier *et al.*, 1998). Denitrification on the other hand occurs where there is no oxygen or where O_2 is partially limited, for example, in waterlogged soils. In this process NO_3^- replaces O_2 as an electron acceptor in soil microbial respiration. NO_3^- and NO_2^- are sequentially reduced to N_2O, NO and N_2 depending on how reducing the conditions are (Firestone *et al.*, 1980). Nitrification and denitrification processes can occur at the same time, at different rates, depending on the soil moisture content (Abbasi and Adams, 2000 (a &

b). Generally denitrification contributes more N_2O than nitrification where O_2 is limited (Bauhus *et al.*, 1996).

In acidic and anaerobic soils, chemical denitrification of nitrite (NO_2^-) with soil organic matter occurs resulting in the formation of NO, N_2O and N_2 (Bouwman, 1990b). Chemical denitrification requires nitrate to be first reduced to nitrite, a reaction that is largely microbial. Natural NO emissions are relatively small compared to the other two N gases emitted by soils (N_2O and N_2) because NO_2^- rarely accumulates naturally in appreciable amounts and Davidson (1993) found that N_2O was 10 or more times greater than the amount of NO produced during denitrification. In microbial denitrification of NO_3^- and NO_2^-, N_2O and N_2 are the dominant products.

8.2.3. Factors affecting N_2O fluxes

Emission of N_2O can occur during either nitrification or denitrification and in some cases, during chemodenitrification (chemical denitrification) of nitrite (NO_2^-). Both nitrification and denitrification can be affected by a number of factors including oxygen availability (nitrification requires oxygen and denitrification occurs only at low oxygen concentration), substrate availability (NH_4^+ for nitrification and carbon and NO_3^- for denitrification). These factors can then be affected by a wide range of additional soil characteristics many of which can be significantly affected by agricultural activities.

Soil moisture is an important factor in N gaseous emissions because it controls the availability of oxygen and the supply of NH_4^+ and NO_2^- to nitrifying bacteria and NO_3^- and NO_2^- to denitrifying bacteria by diffusion (Davidson, 1993). Addition of water to a dry soil results in activation of microbial activity and several workers report higher fluxes of N gases during wet seasons than dry seasons (Davidson *et al.*, 1993). Though N_2O production occurs at all moisture contents, increasing the amount of soil moisture up to and including saturation results in increased N_2O emissions (Freney *et al.*, 1979; Klemedtsson *et al.*, 1988; Riley and Vitousek, 1995; Maag and Vinther, 1996). Increasing soil moisture content inhibits diffusion of O_2 to microorganisms thus enhancing denitrification and it also similarly affects the fluxes of NO, N_2O, CO_2 and other gases from the soil (Davidson, 1993). Different soil moisture parameters have

been measured to assess the effect on emissions. The main parameters used are gravimetric moisture content (Wulf *et al.*, 1999) and water-filled pore space (WFPS) (Davidson, 1993). There are increasingly more measurements of WPFS compared to gravimetric moisture content because WPFS provides a better indication of the likely aeration status of the soil, a parameter which is difficult to determine directly (Riley and Vitousek, 1995). However, Davidson, (1993) reports that both gravimetric moisture content and WPFS are useful predictors of N gas emissions from soils.

Other factors that control N_2O release include N mineralisation, that is, source of mineral N, availability of easily oxidisable carbon and variations in soil temperature. Nitrifying bacteria require an NH_4^+ substrate and denitrifying bacteria require a NO_3^- substrate and many workers have observed elevated emissions after addition of mineral N to soils (Keller *et al.*, 1988; Skiba *et al.*, 1993; Smith *et al.*, 1997; Hall and Matson, 1999, Baggs *et al.*, 2000). Microorganisms involved in the denitrification process require a readily decomposable supply of organic matter as an energy source (Bouwman, 1990b). A higher supply of mineral N and easily oxidisable carbon generally results in higher emissions (Mogge *et al.*, 1998).

Nitrogen gas emissions also depend on soil and ambient temperature (Luo *et al.*, 1999). The nitrification process occurs rapidly at 25 ^{o}C and above and the optimum temperature for denitrification is between 30 and 35 ^{o} C (Bouwman, 1990b). At low temperatures below 5 ^{o}C and temperatures above 40 ^{o}C microbial activity becomes very low. Freney *et al.* (1979) reports that increasing soil temperature up to 37 ^{o} C increases N_2O emissions.

Nitrification proceeds slowly in acidic soils and liming has been observed to enhance N_2O emissions (Yamulki *et al.*, 1997; Mosier *et al.*, 1998). Acid pH in soils under anoxic conditions is known to enhance emission of N_2O compared to the other nitrogenous gases (Bremner and Blackmer, 1978; Firestone *et al.*, 1980).

8.2.4. Methods used for measuring N_2O fluxes

A number of methods are used for measuring N gas emissions. The most commonly used methods are chamber and isotope techniques. Chamber techniques involve the placement or insertion of a sealed chamber into the soil (Denmead, 1979; Conrad *et al.*, 1983; Bouwman, 1990b, Mosier, 1990). The chamber used can either be closed or open. Closed chambers are used for measuring periodic changes of gas with time and with this method, it is possible to measure very small gas fluxes (Bouwman, 1990b). The method is easy to set up and can be used over any period of time. In closed chamber systems the main limitation is that emitted gas can build up, retarding normal gas diffusion from the soil especially if gas sampling is over a long period.

Open chambers, on the other hand, have an inlet for continuously drawing in air to flow over the enclosed area so as to displace emitted gases through an outlet (Mosier, 1990). The environment inside the chamber is therefore close to ambient conditions. With this method it is possible to continuously monitor gas flux from the chamber. The main disadvantage of this method is that artificially high fluxes can arise because of induced air flow. This problem can however be minimised by having a larger inlet compared to the outlet (Denmead, 1979). Samples collected from chamber methods can be analyzed using gas chromatography (Mosier and Mack, 1980; Ryden and Rolston, 1983; Smith and Arah, 1991).

The main weakness of chamber methods is that they cover a very small area and measurement may fail to account for spatial variability of trace gas fluxes (Bouwman, 1990b, Mosier, 1990). This problem can be minimised by using many larger chambers randomly located in the field. The chamber methods can be combined with acetylene (C_2H_2) that inhibits further reduction of N_2O to N_2 gas, enabling the determination of total N-loss (N_2+ N_2O). Isotope methods involve labeling of nitrogen additions using ^{15}N isotope. Mass spectrometry is used to measure ^{15}N remaining in the soil and the gaseous N evolved as ^{15}N. The sensitivity of this method is very high but its main limitation is that it is expensive. The other limitation is that ^{15}N cannot measure loss of N_2O derived from organic matter. The two methods, chamber and isotope techniques,

can be used in the field or in the laboratory using soil cores (Aulakh *et al.*, 1991; Castle *et al.*, 1998; Williams *et al.*, 1998).

Gaseous losses can also be deduced from N balance where plant uptake, leaching losses and N remaining in soil are accounted for. This method can also employ ^{15}N. The last method involves measurement of vertical concentration gradients and diffusion coefficients of N_2O in a soil profile. Evidence however shows that emissions of N_2O are mainly from close to the soil surface (Denmead *et al.*, 1979). In the present study where periodic sampling of N_2O emitted was carried out, the closed chamber method was found to be adequate because they are easy to install and maintain.

Worldwide data on N gaseous emissions from natural ecosystems are accumulating, especially for temperate and moist tropical forests (Vitousek and Matson, 1992). Many gaps however do exist especially for dry and seasonally dry tropical African environments. These ecosystems possibly contribute significant amounts of emissions from forests and woodlands. There is therefore a need to measure N gas emissions because they are an important component in N cycling and N circulation is a critical component of miombo woodland geochemical cycling. Such measurements can also be used to estimate regional and global emissions (Matson and Vitousek, 1987).

8.3. MATERIALS AND METHODS

Samples of N_2O were collected using static and closed plastic chambers with a diameter of 25 cm and a height of 12.5 cm (Figure 8.1 & Plate 8.1). Gas was collected by covering the sampling area with the chamber so as to trap gas emitted from a known area for about an hour. A chisel was used to cut a groove around the chamber and the edges were pushed about 3 cm into the soil. Gas (15 ml) was drawn from the chamber using an air-tight syringe and transferred into evacuated aluminium vials through a septum.

At Mukuvisi Woodlands, gas samples were collected at 3 points about 80 m apart within each experimental area, along the middle transect running through the burnt area (Muk-Burn), the protected area (Muk-Prot), and the protected grassland area (Muk-Grass). Gas was also collected from three points along the transect running through the deforested burnt area (Muk-Def). Control samples were collected from bare areas (Muk-Con). At Henderson Research Station, gas samples were collected from one central point in each experiment area (Hen-Up, Hen-Mid and Hen-Low) along each transect, making total of 3 sampling points within each experiment area. Control gas samples were collected from bare areas (Hen-Con) in a fallow field.

At each sampling point at Mukuvisi and Henderson, 3 replicate gas samples were collected. The next sampling was carried out within the same area on a different position. A fourth sample was collected from the air so as to measure the ambient levels of N_2O. N_2O was analyzed using gas chromatography at the Scottish Agricultural College in Edinburgh. Nitrous oxide concentrations were determined by comparing peak area for samples and standards.

Fluxes were calculated by subtracting the ambient N_2O concentration from the concentration of gas in the closed chamber. N_2O fluxes were then calculated as follows:

$$\mathbf{N_2O\ flux} = \frac{(ppm\ N_2O\ change * conversion\ factor * volume\ of\ headspace)}{(area\ of\ headspace * time\ of\ enclosure)}$$

Topsoil temperature, within 5 cm depth, was measured while collecting gas samples so as to assess the effect of soil temperature on N_2O emissions. Soil samples were also collected from the top 10 cm, from the points where gas samples were collected. Each position sampled was marked so that sampling was not repeated at the same spot. The 3 samples were mixed and analyzed for NH_4^+-N and NO_3^--N using the method described in section 2.2.4 iv). Part of the mixed sample was used to determine gravimetric moisture content.

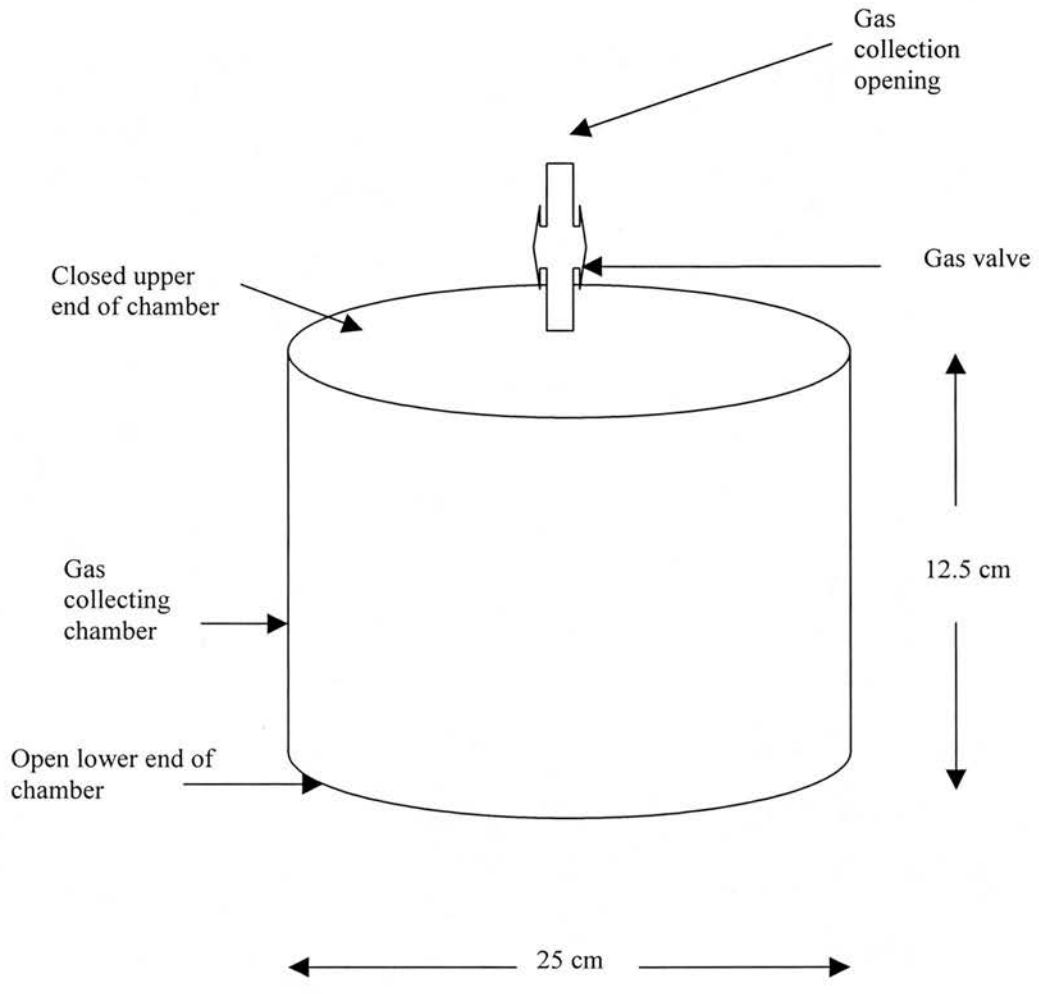


Figure 8.1. A diagram of a gas collection unit used in the measurement of N_2O emissions. A chisel was used to cut a groove around the chamber and the edges were pushed about 3 cm into the soil. A known volume of gas was drawn from the chamber using an air-tight syringe through the gas collecting opening controlled by a valve.

Plate 8.1. A gas collection unit used in the measurement of N_2O emissions at Mukuvisi Woodlands, Muk-Prot experiment area. A chisel was used to cut a groove around the chamber and the edges were pushed about 3 cm into the soil. A syringe in the picture was used for collecting gas from the closed static chamber.

Gravimetric moisture was determined immediately after getting to the laboratory. About 50 g of soil was weighed into a beaker and placed in an oven for 48 hours at 105 ^{o} C. Soil was re-weighed and the amount of moisture calculated and expressed as a percentage of dry soil. NH_4^+-N and NO_3^--N were analysed as outlined in section 3.2.2 (iv).

8.4. RESULTS AND DISCUSSION

8.4.1. Nitrogen loss through N_2O emissions

N_2O fluxes were higher in the wet season compared to the dry season at both study areas. Addition of rainfall gave rise to an increase in NH_4^+-N and NO_3^--N in soils as a result of increased N mineralisation and nitrification (Figure 8.2-10).

Nitrous oxide fluxes at Mukuvisi Woodlands were very low on the 22nd October 2000, that is, day 0, before the onset of the rains. After the onset of the rain season, in late October, N_2O fluxes increased (Figure 8.2-6). Jancinthe and Dick (1997) also observed increased fluxes of N_2O after rainfall events. Fluxes peaked between days 15 and 45 after the beginning of the rain season. The highest maximum flux was at Muk-Prot (33.2 $\mu gN/m^2/hr$), followed by Muk-Burn (24.7 $\mu gN/m^2/hr$), Muk-Grass (22.8 $\mu gN/m^2/hr$), Muk-Def (14.3 $\mu gN/m^2/hr$) with the lowest at Muk-Con (9.3 $\mu gN/m^2/hr$). As expected, Muk-Prot had the highest N_2O fluxes because this experiment area is likely to have higher amounts of easily oxidisable carbon and mineral N from the freshly fallen litter. Availability of easily oxidisable carbon and mineral N are known to increase N_2O fluxes (Mogge *et al.*, 1998). At Muk-Burn some of the easily oxidisable carbon and mineral N is lost through burning. At Muk-Grass and Muk-Def and Muk-Con litter inputs are not as high as Muk-Prot and Muk-Burnt which have more woody vegetation. Thereafter, fluxes gradually decreased to close to 0 $\mu gN/m^2/hr$. At low moisture contents small amounts of N_2O were lost confirming observations by other workers that production of N_2O is continuous at all moisture contents and moisture is an important controlling factor of N_2O emissions (Freney *et al.*, 1979).

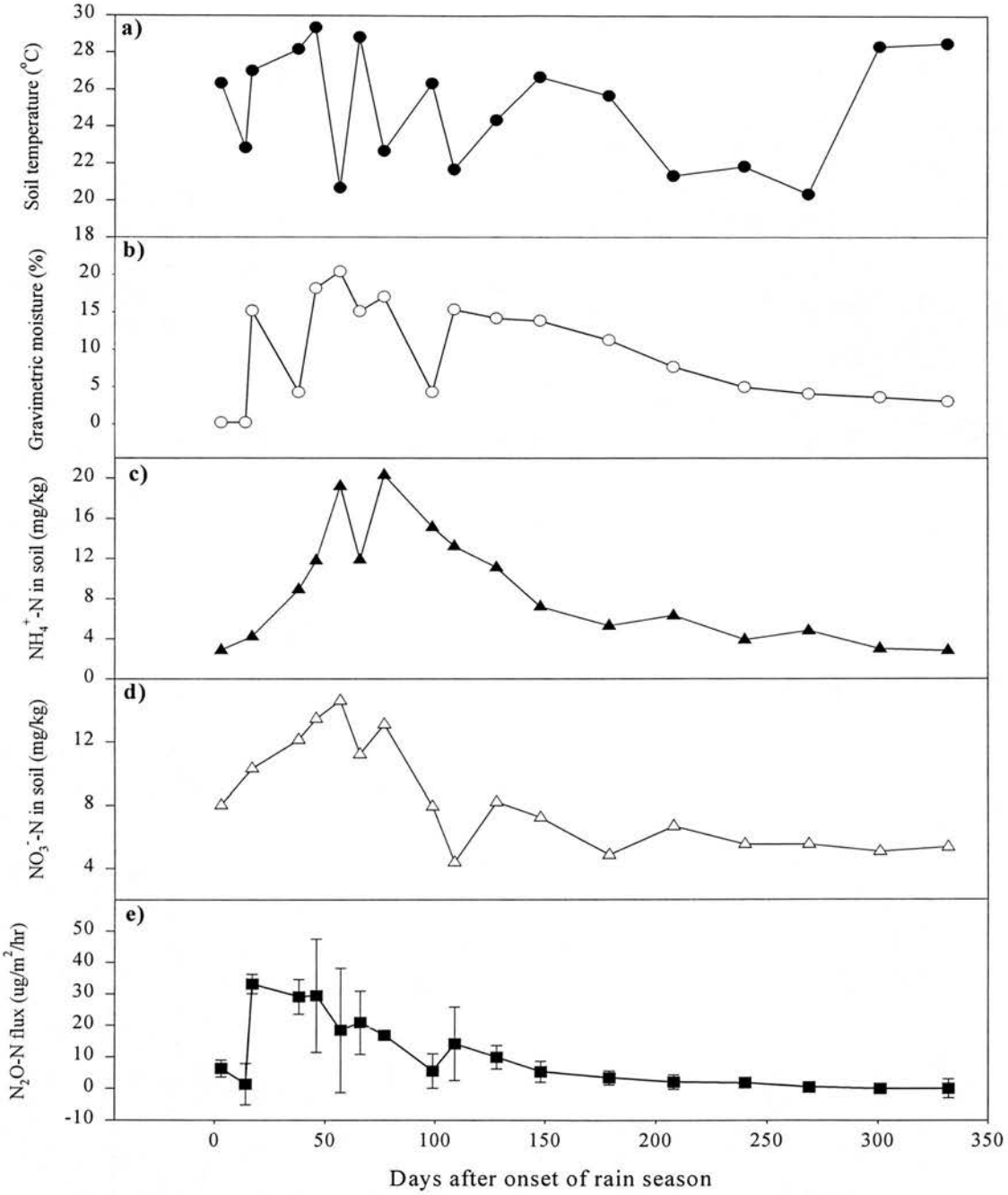


Figure 8.2. Changes in a) temperature, b) soil moisture, c) NH_4^+-N d) NO_3^--N and e) N_2O-N emission at Muk-Prot from the beginning of the rain season in November 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

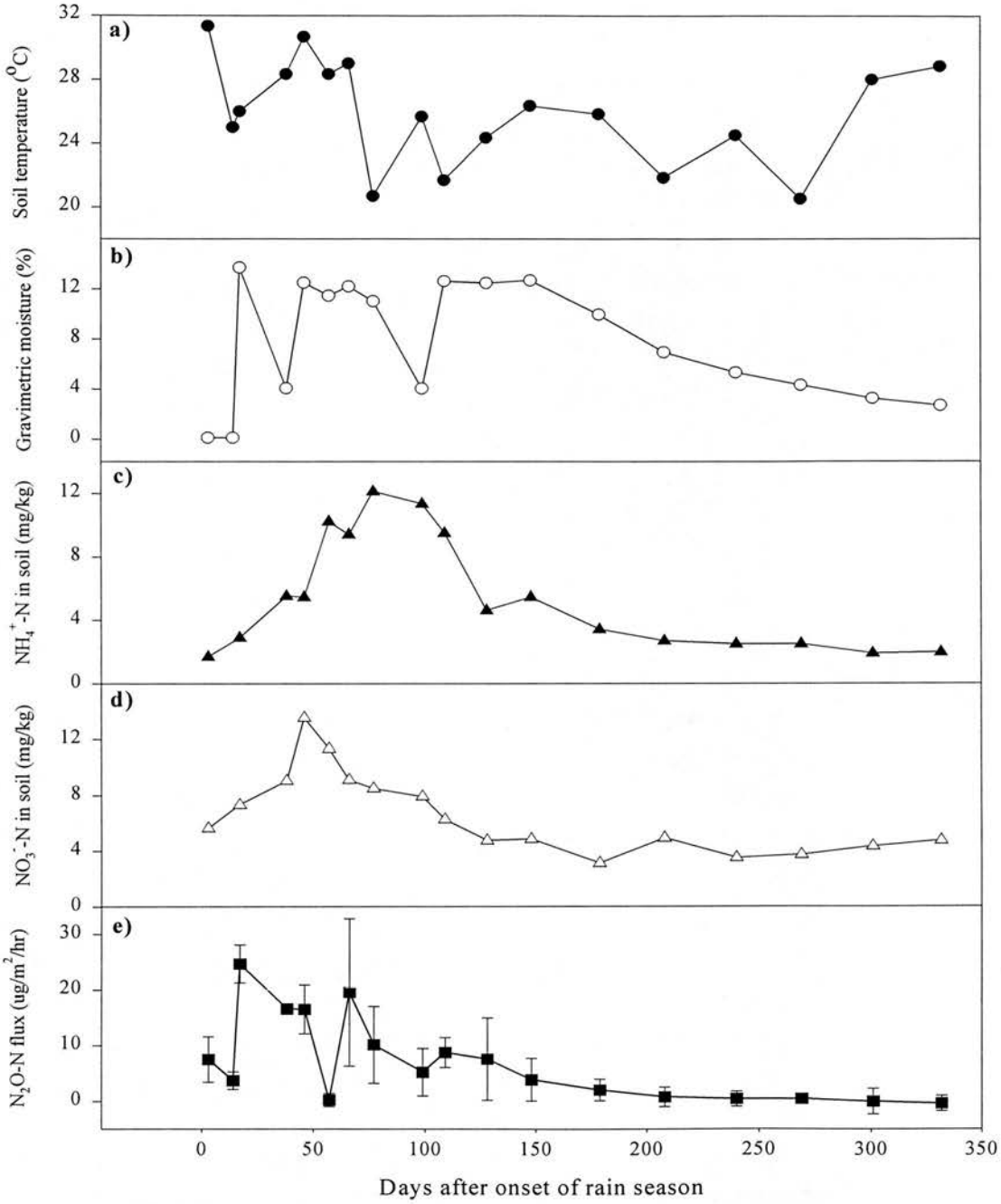


Figure 8.3: Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emissions at Muk-Burn from the beginning of the rain season in November 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

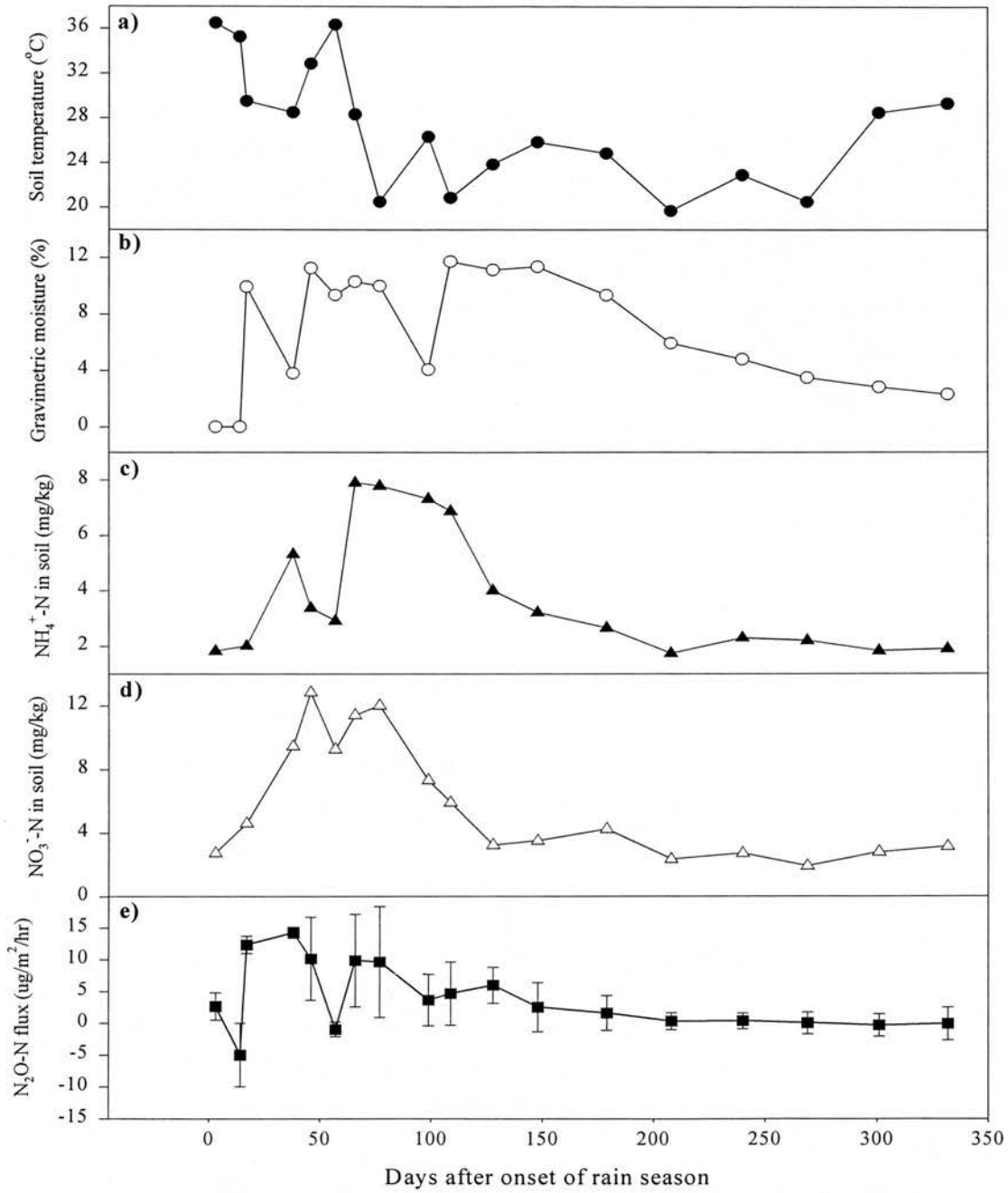


Figure 8.4. Changes in a) temperature, b) soil moisture, c) NH_4^+-N d) NO_3^--N and e) N_2O-N emissions at Muk-Def from the beginning of the rain season in November 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

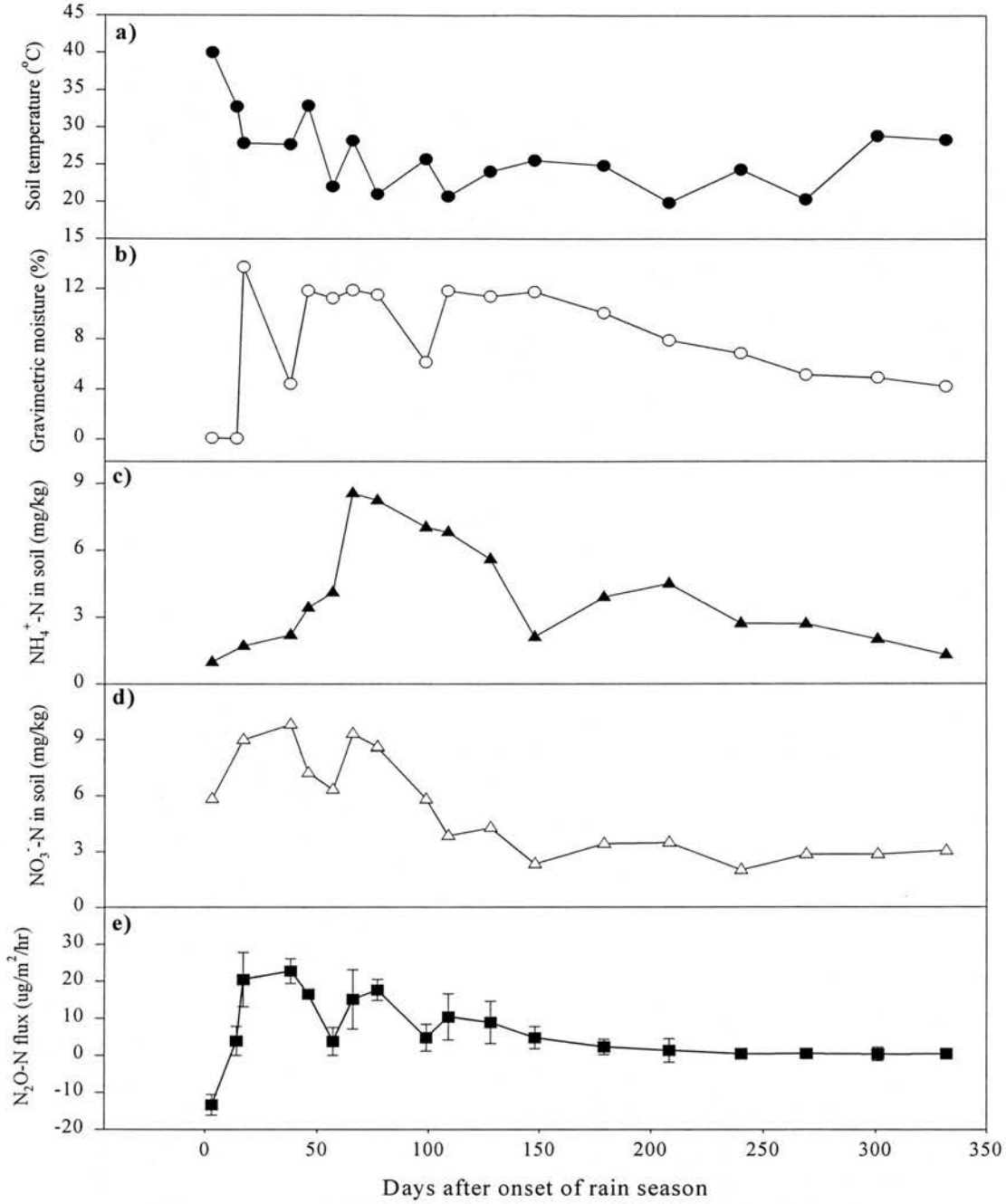


Figure 8.5. Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emissions at Muk-Grass from the beginning of the rain season in November 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

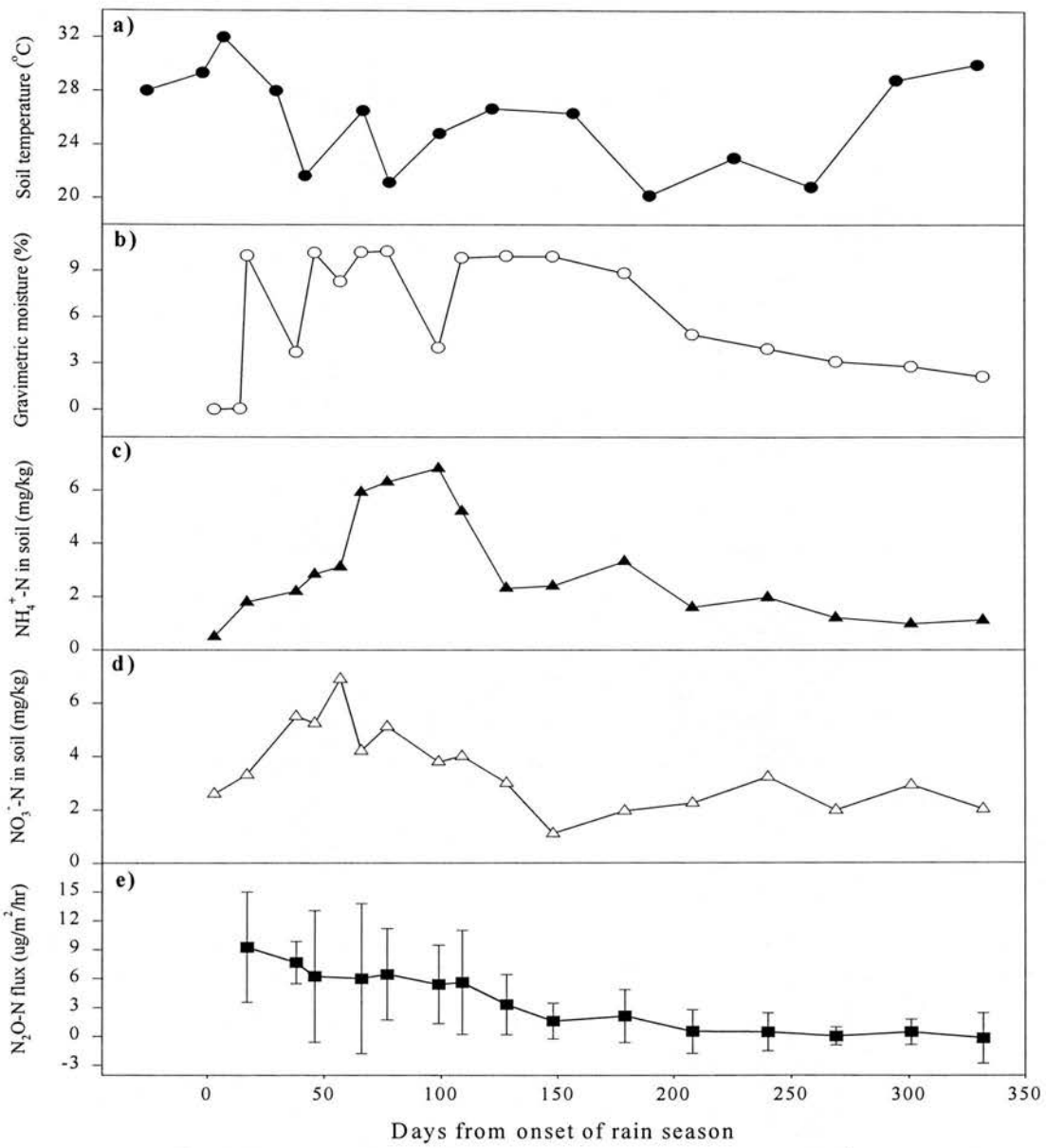


Figure 8.6. Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emissions at Muk-Con from the beginning of the rain season in November 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

At Henderson Research Station, the highest maximum N_2O flux was at Hen-Low (41.9 $\mu gN/m^2/hr$) experiment area, followed by Hen-Mid (27.3 $\mu gN/m^2/hr$), Hen-Up (15.1 $\mu gN/m^2/hr$) and Hen-Con (10.1 $\mu gN/m^2/hr$) with the lowest flux (Figure 8.7-10). Trends between soil moisture and mineral N and N fluxes observed at Mukuvisi Woodlands were also evident at Henderson sites (Figures 8.7-10) over the 12 months. Higher amounts of moisture and mineral N at the beginning of the rain season corresponded to higher N_2O fluxes. Of the experiments sites at the two study areas, Mukuvisi and Henderson, Hen-Low (41.9 $\mu gN/m^2/hr$) had the highest maximum N_2O flux and Muk-Con (9.3 $\mu gN/m^2/hr$) had the lowest. There was no clear relationship between temperature and N_2O fluxes. At the beginning and end of the rain season, at both Mukuvisi and Henderson study areas, some negative fluxes were obtained, showing that N_2O oxide emitted can be used as an electron acceptor by microorganisms resulting in the formation of N_2.

The N_2O fluxes measured over the 12 month period were plotted against soil temperature, gravimetric moisture content, NH_4^+-N and NO_3^- -N to find out if there is any relationship. No linear relationship was observed at Mukuvisi Woodlands experimental sites except for the plot of N_2O flux against NO_3^--N in Muk-Prot and Muk-Con. The R^2 in these areas were 61 and 58 % respectively. The data was therefore split into the rainy season and the dry season. The rainy season was from November 2000 to March 2001 and the dry season was from April 2001 to September 2001 at Mukuvisi Woodlands. The N_2O fluxes were regressed with soil temperature, gravimetric moisture content, NH_4^+-N and NO_3^- -N (Figures 8.11-12). No clear relationships were established during the rain season at Mukuvisi experimental areas. Other researchers suggest the use of the parameter, water-filled pore space (WFPS) (Davidson, 1993; Riley and Vitousek, 1995). It was not possible to convert gravimetric soil moisture to WFPS because bulk density was not measured at the study sites. However, the dry season which started from the end of the rain season in April 2001 to September 2001 showed a positive linear relationship between N_2O fluxes and gravimetric soil moisture with an $R^2 > 80\%$ at all experimental areas (Figures 8.12b). Soil moisture is an important requirement for microbial activity and many researchers

report an increase in N_2O fluxes with an increase in moisture (Conrad *et al.*, 1983; Baggs *et al.*, 2000). During the dry season, as the soil moisture decreases, N_2O fluxes also decreased. A positive linear relationship between N_2O fluxes and NH_4^+-N (Fig. 8.12c) was also observed at all Mukuvisi experimental sites with the exception of Muk-Grass. NH_4^+-N is an important factor in the production of N_2O during the nitrification process. High amounts of NH_4^+-N result in elevated N_2O fluxes (Bouwman, 1990; Davidson, 1993). It is possible that no relationship was evident at Muk-Grass, where there is waterlogging in places, because denitrification which is the likely dominant process, requires NO_3^--N. Logarithmically transformed N_2O fluxes showed a similar pattern during the rainy season (Fig. 8.13). A plot of N_2O fluxes against gravimetric soil moisture similarly showed a positive linear relationship ($R^2 > 60\%$) during the dry season (Fig. 8.14b).

Similar plots for Henderson experimental sites during the rainy season (Figures 8.15) showed no linear relationships between N_2O fluxes with soil temperature, gravimetric moisture content, NH_4^+-N and NO_3^--N. During the dry season, gravimetric soil moisture showed a positive linear relationship at all experimental sites ($R^2 > 60$ %), a pattern also observed at the Mukuvisi sites. It was also observed that N_2O fluxes had a positive linear relationship with NH_4^+-N and NO_3^--N with the exception of Hen-Con (Fig. 8.16a) and Hen-Up (Fig. 8.16d). Log-transformed N_2O fluxes (Fig. 8.17) during the rain season showed a similar pattern as the untransformed fluxes. During the dry season log-transformed N_2O fluxes also had a positive linear relationship with soil gravimetric moisture (Fig. 8.18b). From the results obtained from Mukuvisi and Henderson experimental sites, logarithmic transformation did not improve the relationship between N_2O fluxes and the factors soil temperature, gravimetric moisture content, NH_4^+-N and NO_3^--N.

It is surprising that in spite of the increased N_2O fluxes during the rainy season (Fig.8.2-10) no clear relationship was obtained between N_2O fluxes and temperature, NH_4^+-N, NO_3^--N and soil moisture at Mukuvisi and Henderson experimental sites (Fig. 8.11, 13, 15 & 17). The NH_4^+-N, NO_3^--N and moisture were measured from the soil. It is

however possible that some N_2O fluxes could have been directly from litter. This distorts any relationship that may be present because fluxes directly from litter are not related to the mineral N and moisture in the soil. During the dry season, it is likely that there is less emission from the litter because the surface litter dries out quickly whereas soil moisture changes gradually. During the dry season nitrification is likely to be the dominant N_2O forming process whereas during the rain season denitrification also contributes to the N_2O-N fluxes.

Multiple regression analysis was carried out for all the experimental areas for the rain season (October to March) and the dry season (April to September) (Table 8.1). All the equations for the dry season had very high R^2 values, greater than 77 %. For the wet season only Muk-Prot, Hen-Low and Hen-Con had $R^2 > 50\%$. It could be that during the rainy season more N_2O release was a result of denitrification and therefore available-C would be important. In this study available carbon was not measured; such measurements could have probably explained some of the variation in N_2O emission during the wet season. During the dry season, nitrification is likely to be the dominant process and therefore changes mainly in moisture, NO_3^- and NH_4^+ could account for the variation in N_2O emissions.

Some authors have observed that simple linear regression analysis may not be appropriate for proper interpretation of the effect of soil moisture and other factors on N_2O fluxes (Davidson, 1993). In this study the changes in temperature, gravimetric moisture content, NH_4^+-N and NO_3^- -N and N_2O fluxes were plotted with time over the rain season (Figures 8.2-10). From these graphs the soil gravimetric moisture content peaks and troughs generally correspond to N_2O flux peaks and troughs during approximately the first 100 days of the rain season. It was evident that moisture content is an important controlling factor in N_2O emissions and similar results have been reported in other studies (Freney *et al.*, 1979; Davidson *et al.*, 1993; Choudhary *et al.*, 2001).

Table 8.1. Relationship between N_2O-N fluxes (F µg/m2/hr) and temperature (T ^oC), gravimetric soil moisture (M %), NH_4^+-N (NH mg/kg) and NO_3^--N (NO mg/kg) at Mukuvisi Woodlands and Henderson Research Station experiment areas. Regression equations for the dry season had very high R^2 values.

Site	Rain season		Dry season	
	Regression equation	R^2 (%)	Regression equation	R^2 (%)
Muk-Prot	$F = 0.256 + 0.019T + 0.027M + 0.02\ NH_4^+ + 0.36NO_3^-$	67.6	$F = 4.47 - 0.246T + 0.369M - 0.663\ NH_4^+ + 0.356\ NO_3^-$	99.3
Muk-Burn	$F = 3.40 - 0.076T - 0.007M - 0.101\ NH_4^+ + 0.039\ NO_3^-$	21.8	$F = -2.21 + 0.055T + 0.083M - 0.019\ NH_4^+ + 0.084\ NO_3^-$	90.8
Muk-Def	$F = 3.20 - 0.074T - 0.033M - 0.131\ NH_4^+ + 0.073\ NO_3^-$	34.7	$F = -3.15 + 0.133T + 0.193M - 0.696\ NH_4^+ - 0.042\ NO_3^-$	95.6
Muk-Grass	$F = 0.09 + 0.011T + 0.019M - 0.005\ NH_4^+ + 0.074\ NO_3^-$	48.2	$F = -1.01 - 0.027T + 0.171M - 0.166\ NH_4^+ + 0.293\ NO_3^-$	99.5
Muk-Con	$F = 0.426 + 0.006T - .001M - 0.006\ NH_4^+ + 0.053\ NO_3^-$	23.1	$F = -4.31 + 0.011T + 0.447M - 0.478\ NH_4^+ + 0.965\ NO_3^-$	92.8
Hen-Up	$F = 0.50 - 0.005T + 0.007M - 0.023\ NH_4^+ + 0.081\ NO_3^-$	40.1	$F = -4.66 + 0.145T - 0.012M + 0.547\ NH_4^+ - 0.016\ NO_3^-$	98.5
Hen-Mid	$F = 1.18 - 0.034T + 0.001M - 0.016\ NH_4^+ - 0.097\ NO_3^-$	43.5	$F = 0.766 + 0.023T + 0.171M - 0.57\ NH_4^+ - 0.159\ NO_3^-$	99.9
Hen-Low	$F = -2.28 + 0.072T + 0.018M + 0.024\ NH_4^+ + 0.089\ NO_3^-$	50.6	$F = 0.08 + 0.013T + 0.218M + 0.471\ NH_4^+ - 0.02\ NO_3^-$	94.5
Hen-Con	$F = 1.68 - 0.026T - 0.013M - 0.088\ NH_4^+ + 0.062\ NO_3^-$	96.2	$F = -1.39 + 0.018T + 0.024M - 0.183\ NH_4^+ + 0.462\ NO_3^-$	77.7

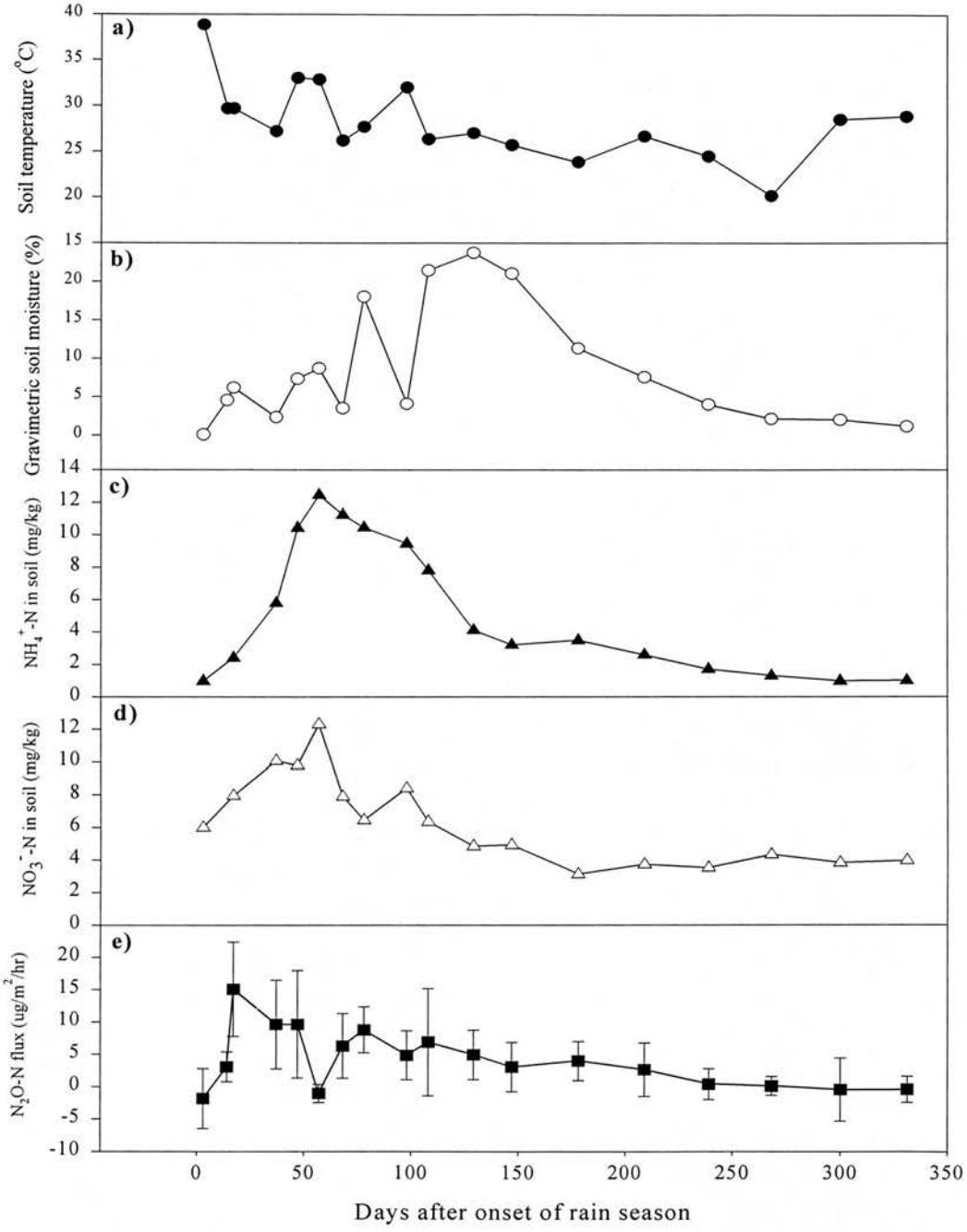


Figure 8.7. Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emission at Hen-Up from the beginning of the rain season in October 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

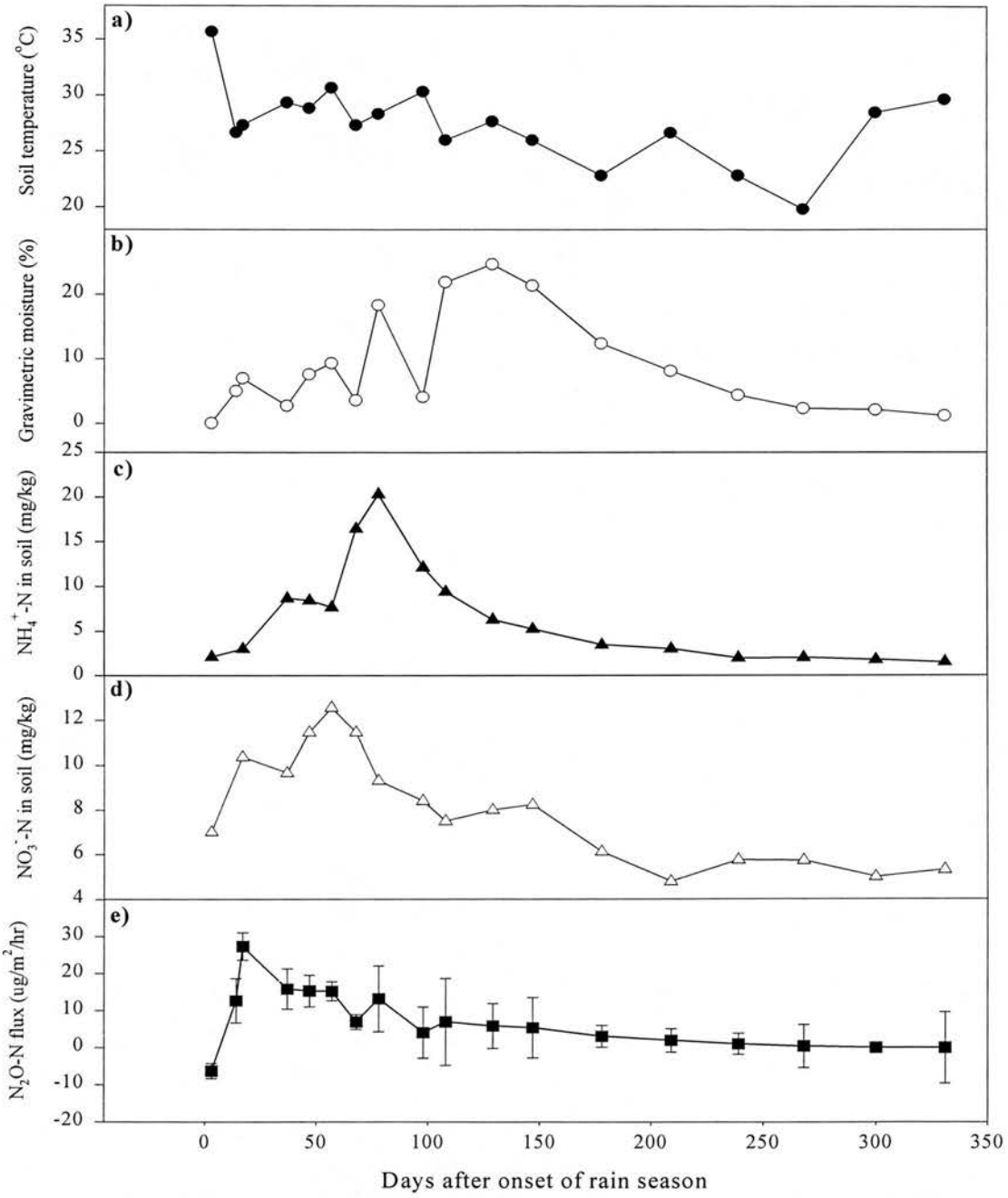


Figure 8.8. Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emissions at Hen-Mid from the beginning of the rain season in October 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

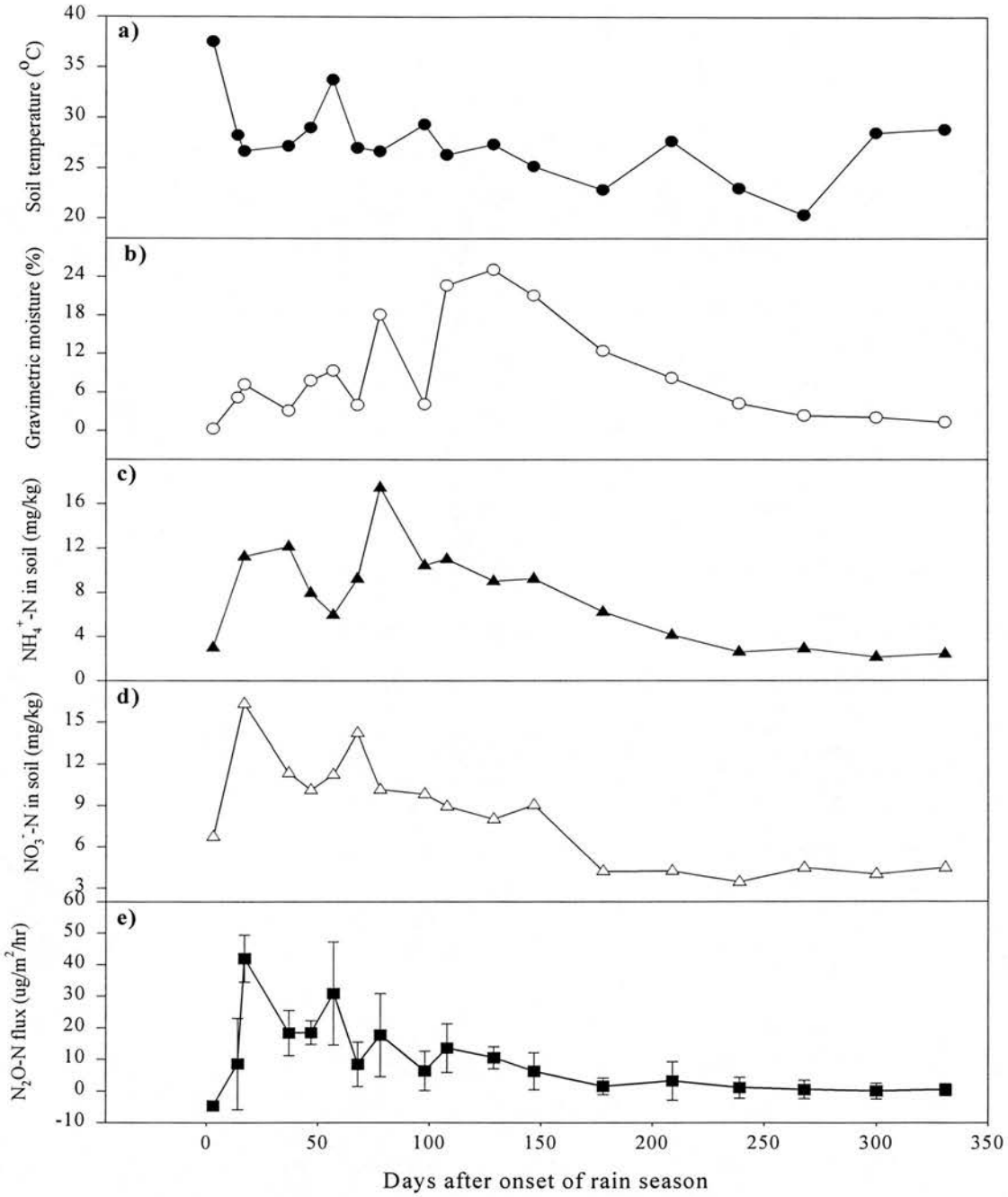


Figure 8.9. Changes in a) temperature b) soil moisture c) NH_4^+-N d) NO_3^--N and N_2O-N emissions at Hen-Low from the beginning of the rain season in October 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N were high. Temperature appeared to have no effect on gas fluxes.

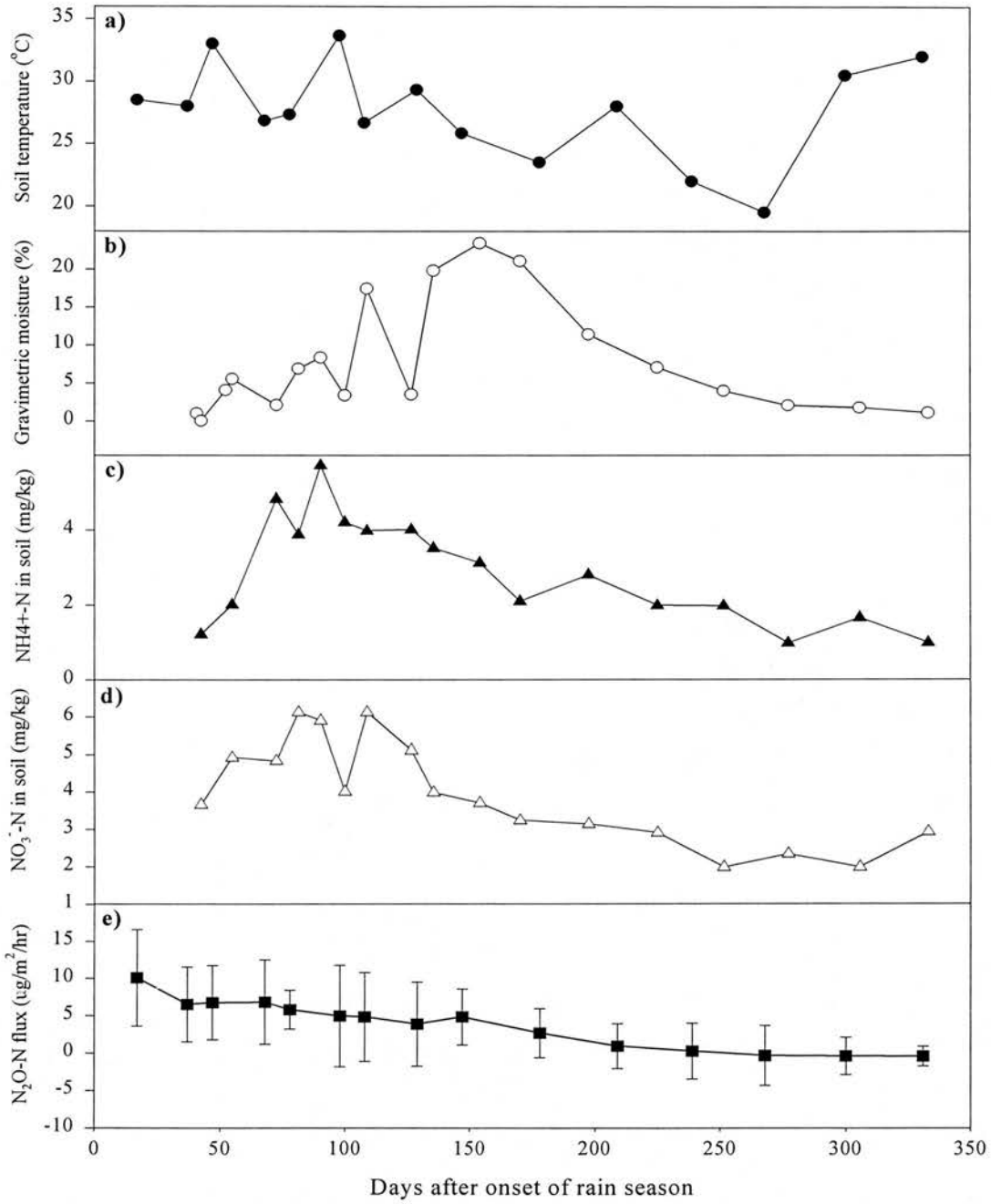


Figure 8.10. Changes in a) temperature, b) soil moisture, c) NH_4^+-N, d) NO_3^--N and e) N_2O-N emission at Hen-Con from the beginning of the rain season in October 2000 to the dry season in September 2001. Higher fluxes occurred during the rain season when soil moisture, NH_4^+-N and NO_3^--N where high. Temperature appeared to have no effect on gas fluxes.

The amounts of NH_4^+-N and NO_3^- -N were generally higher during the same period when fluxes were highest. Addition of water to a dry soil increases N mineralisation and nitrification resulting in increased NH_4^+-N and NO_3^- -N (Davidson *et al.*, 1993). After day 100, there was a general decrease in soil NH_4^+-N and NO_3^- -N which corresponded to a general decline in N_2O fluxes. Mineral N, soil moisture content and N_2O fluxes are inter-related. The mineralisation of organic N by soil microbes correlates with soil water content and the availability of mineral N in turn determines N_2O fluxes. In the range of water content encountered at the field sites in Zimbabwe, it would be anticipated that most N_2O would be from the processes nitrification and denitrification. Denitrification would be expected to dominate after a heavy rainfall event when the soil is saturated and as the soil dries out nitrification is expected to dominate.

No relationship could be deduced between N_2O fluxes and soil temperature. However laboratory experiments by other workers have shown that increasing temperature to 37 ^{o} C has the effect of increasing N_2O fluxes (Freney *et al.* 1979). In the field the effect of temperature may not be clear because there are other factors that may have a greater effect or may interact with temperature. In laboratory conditions, studying the effect of a factor is easier because other factors can be controlled unlike in the field where this is very difficult.

Mean emission rates from both Henderson and Mukuvisi study sites ranged from 2.71 to 6.20 $\mu gN/m^2/hr$ (Table 8.2). Differences between means were not significant with the exception of Muk-Prot and Hen-Con ($p < 0.05$). The highest amount of N_2O-N was lost from Hen-Low with the lowest in Hen-Con (Table 8.2). The order of total annual N_2O-N lost from the highest to the lowest was Hen-Low > Muk-Grass > Muk-Prot > Muk-Burn > Hen-Mid > Muk-Def > Hen-Up > Muk-Con > Hen-Con (Table 8.2). Hen-Low is on the lower slope topographic position where water accumulates from the upper slope experimental areas. There were few faint mottles in the sub-soils indicating that there is restricted drainage. Denitrification is therefore likely to be higher in this experimental area resulting in more N_2O-N emissions than the other areas.

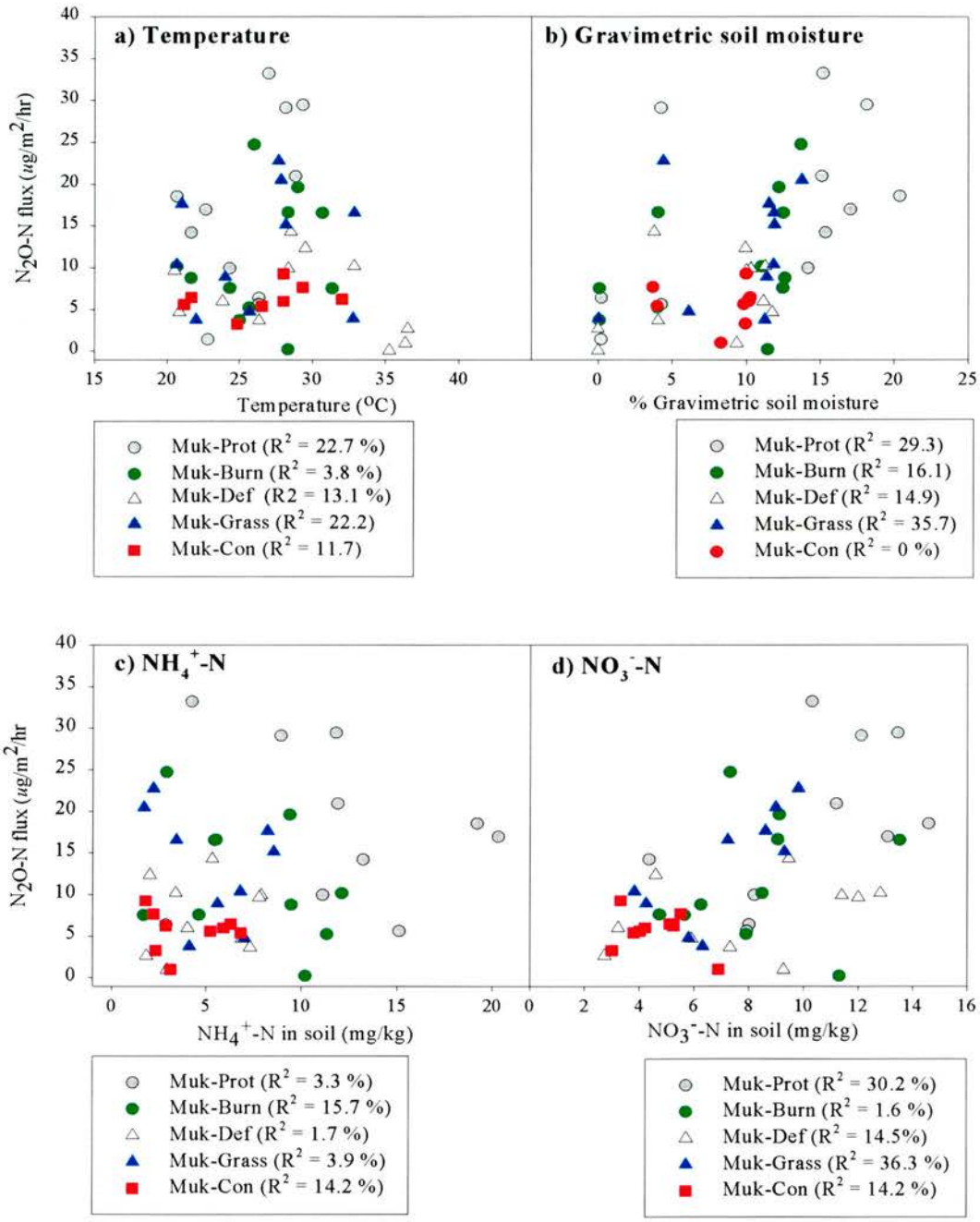


Figure 8.11. Relationship between nitrous oxide fluxes (without log-transformation) and a) temperature (°C), b) % gravimetric soil moisture, c) NH_4^+-N (mg/kg) and d) NO_3^--N at Muk-Prot, Muk-Burn, Muk-Def, Muk-Grass and Muk-Con during the rainy season from November 2000 to March 2001. No clear linear relationship was observed.

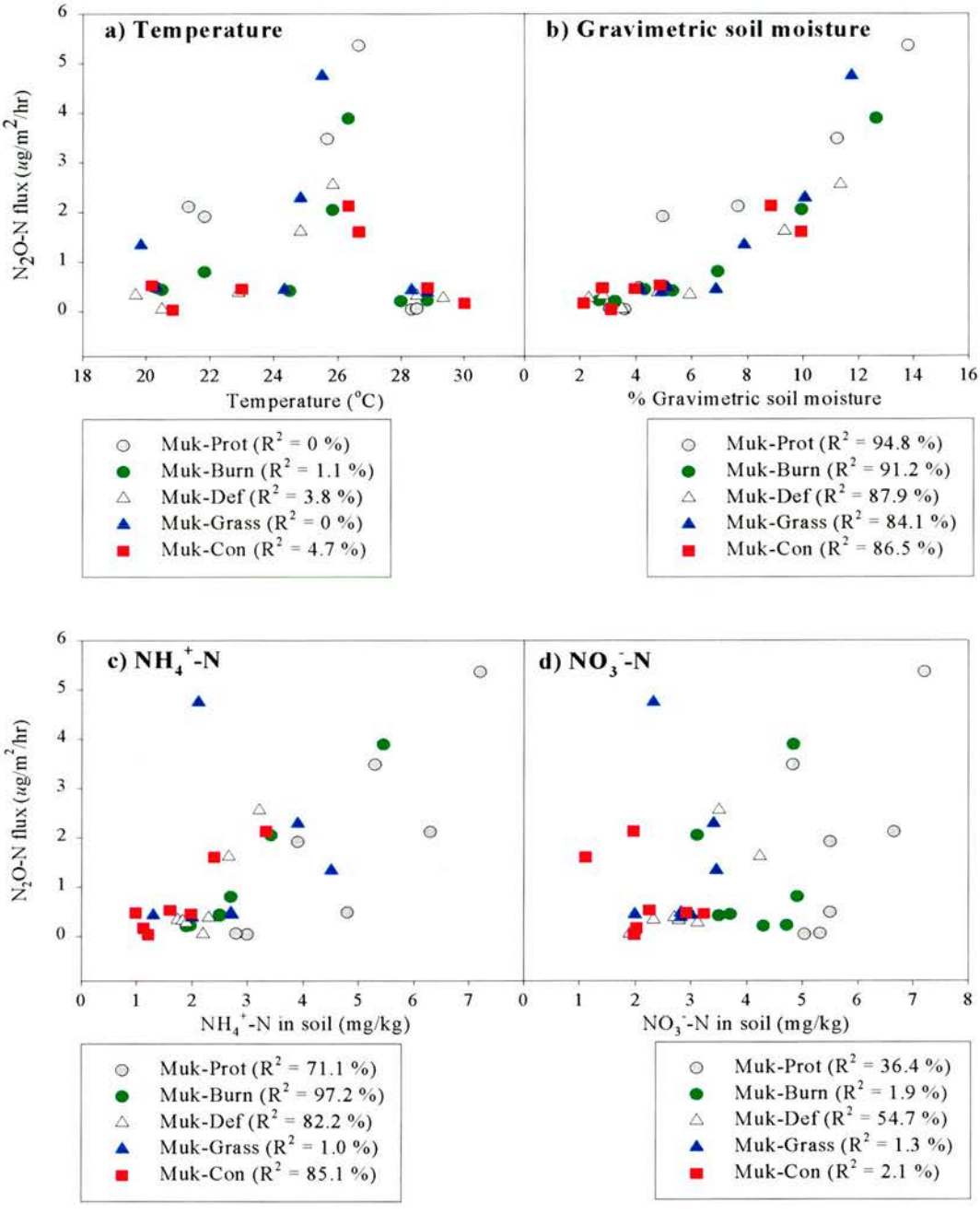


Figure 8.12. Relationship between nitrous oxide fluxes (without log-transformation) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and d) NO_3^--N (mg/kg) at Muk-Prot, Muk-Burn, Muk-Def, Muk-Grass and Muk-Con during the dry season from April 2001 to September 2001. At all experimental sites, there was a positive linear relationship between N_2O emissions and soil moisture; $R^2 > 80\%$.

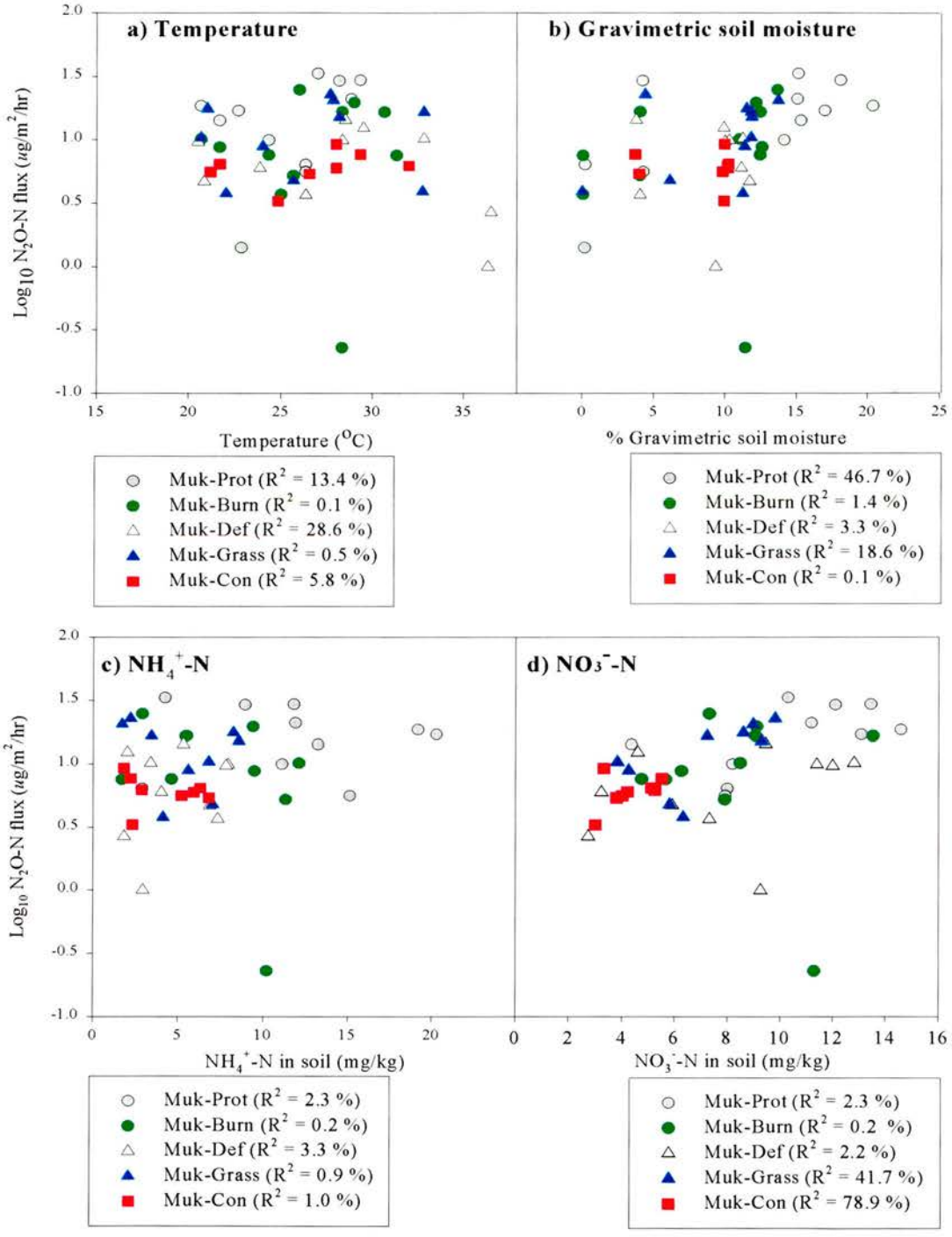


Figure 8.13. Relationship between nitrous oxide fluxes (log-transformed) and a) temperature b) gravimetric soil moisture, c) NH_4^+-N (mg/kg) and d) NO_3^--N (mg/kg) at Muk-Prot, Muk-Burn, Muk-Def, Muk-Grass and Muk-Con during the rain season from November 2000 to March 2001. No clear linear relationship was observed.

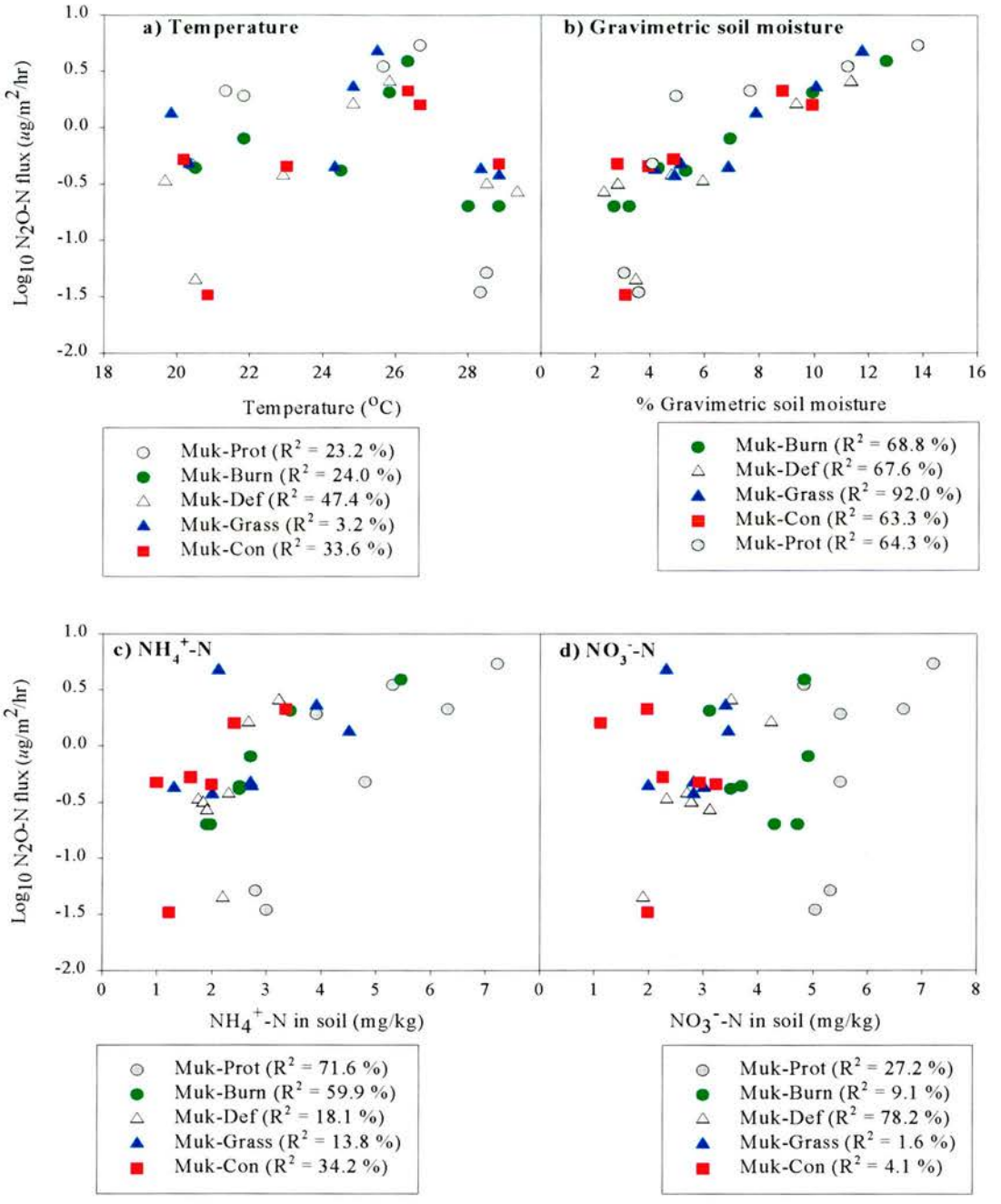


Figure 8.14. Relationship between nitrous oxide fluxes (log-transformed) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and d) NO_3^--N (mg/kg) at Muk-Prot, Muk-Burn, Muk-Def, Muk-Grass and Muk-Con during the dry season from April 2001 to September 2001. At all experiment there was a positive linear relationship between N_2O emissions and soil moisture; $R^2 > 60$ %.

Table 8.2. Mean emissions and estimated annual N lost as N_2O gas from Mukuvisi Woodlands and Henderson Research Station during the period from October 2000 to September 2001. Mean emissions were calculated from monthly emissions. Annual loss estimate is a product of the mean emission and the number of days in a year. Additions in throughfall is the total amount of N in water passing through the canopy. (SE – standard error of the mean emission; ♣ - direct nutrient addition from rainfall; * - area does not have litter inputs)

Experiment Area	Mean emission (SE) ($\mu g/m^2/hr$)	Annual N_2O-N loss ($mg/m^2/year$)	Annual N additions in throughfall ($mg/m^2/year$)	Annual N additions in litter ($mg/m^2/year$)
Muk-Prot	**5.72** (2.55)	49.7	1170	6520
1 Muk-Burn	**4.86** (2.10)	42.2	804	4360
Muk-Def	**3.18** (1.21)	27.7	747 ♣	*
Muk-Grass	**5.99** (2.11)	52.1	747 ♣	*
Muk-Con	**2.86** (0.98)	24.9	747 ♣	*
Hen-Up	**2.87** (0.99)	25.0	581	4000
Hen-Mid	**4.30** (1.91)	37.4	629	3660
Hen-Low	**6.20** (2.46)	53.9	731	4240
Hen-Con	**2.71** (0.91)	23.6	571♣	*

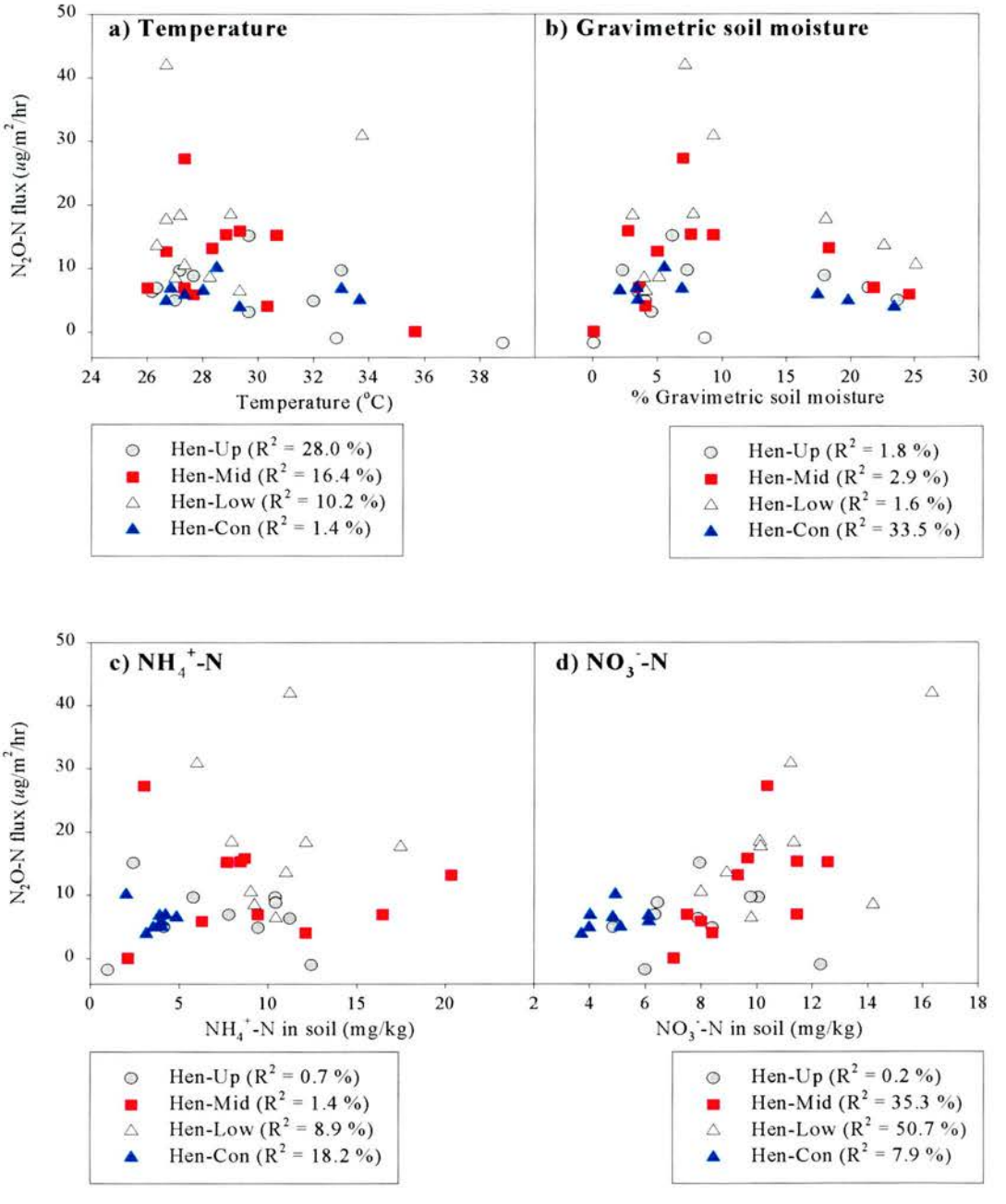


Figure 8.15. Relationship between nitrous oxide fluxes (without log-transformation) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and NO_3^--N (mg/kg) at Hen-Up, Hen-Mid, Hen-Low and Hen-Con during the rainy season from October 2000 to March 2001. No clear linear relationship was observed.

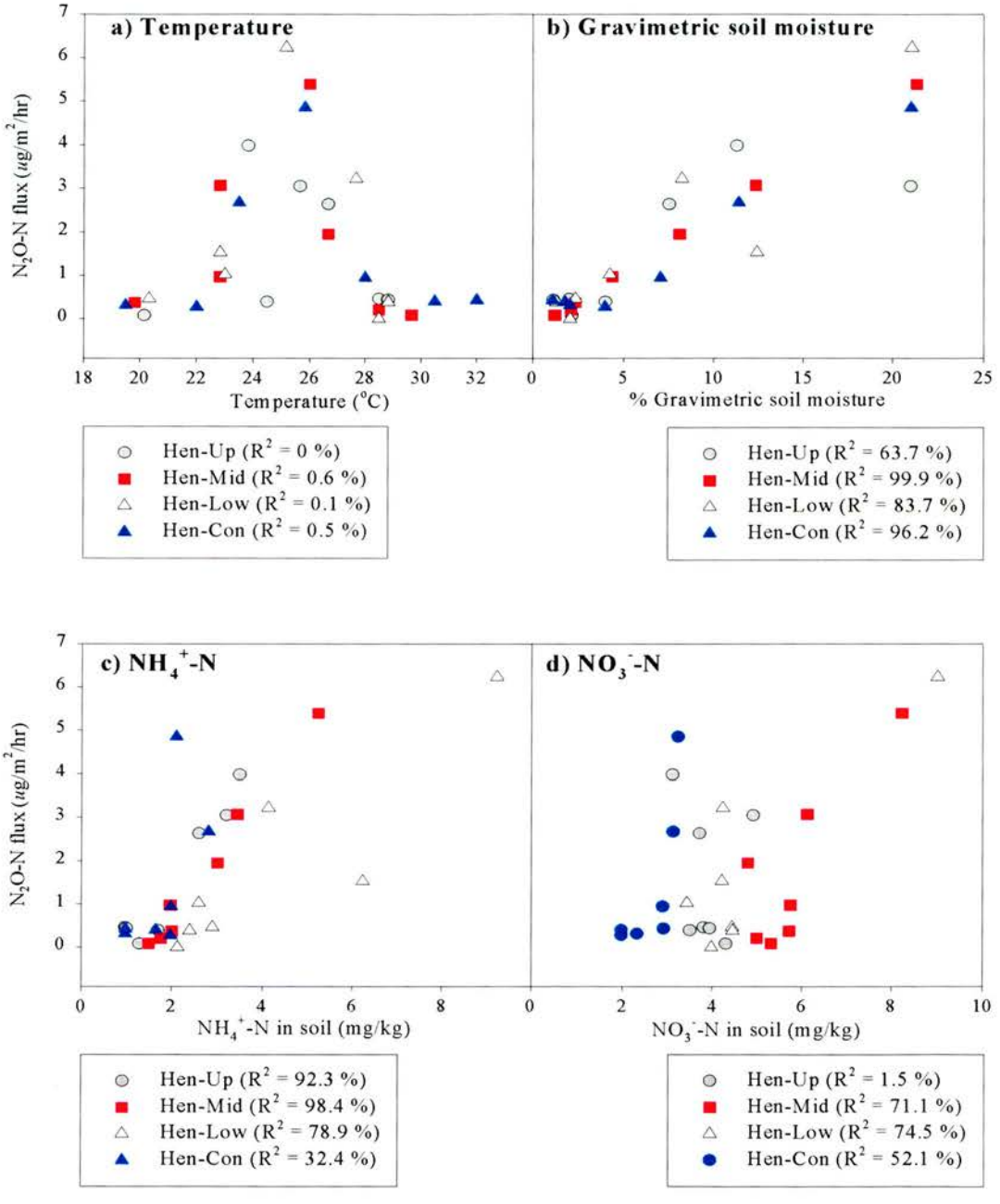
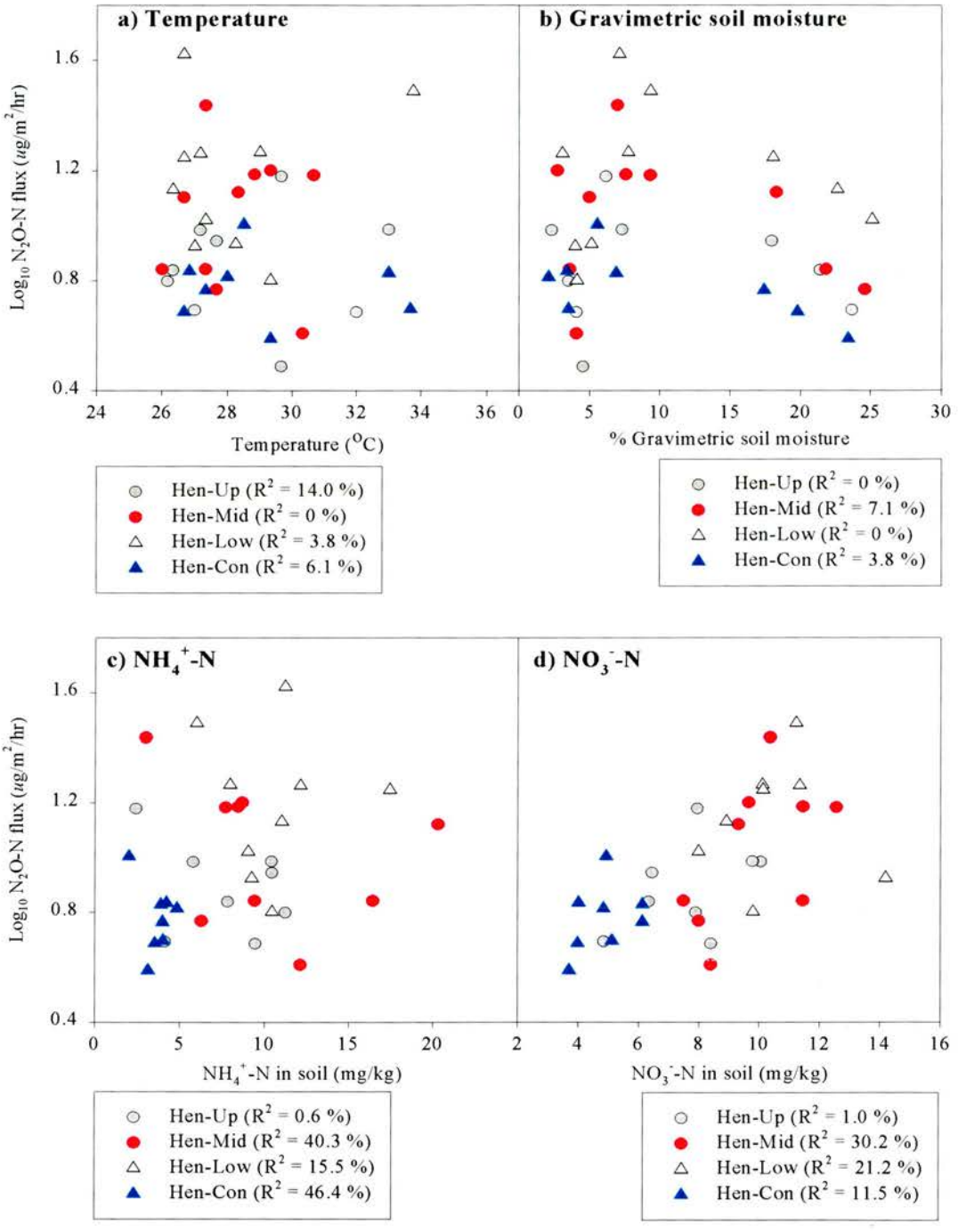
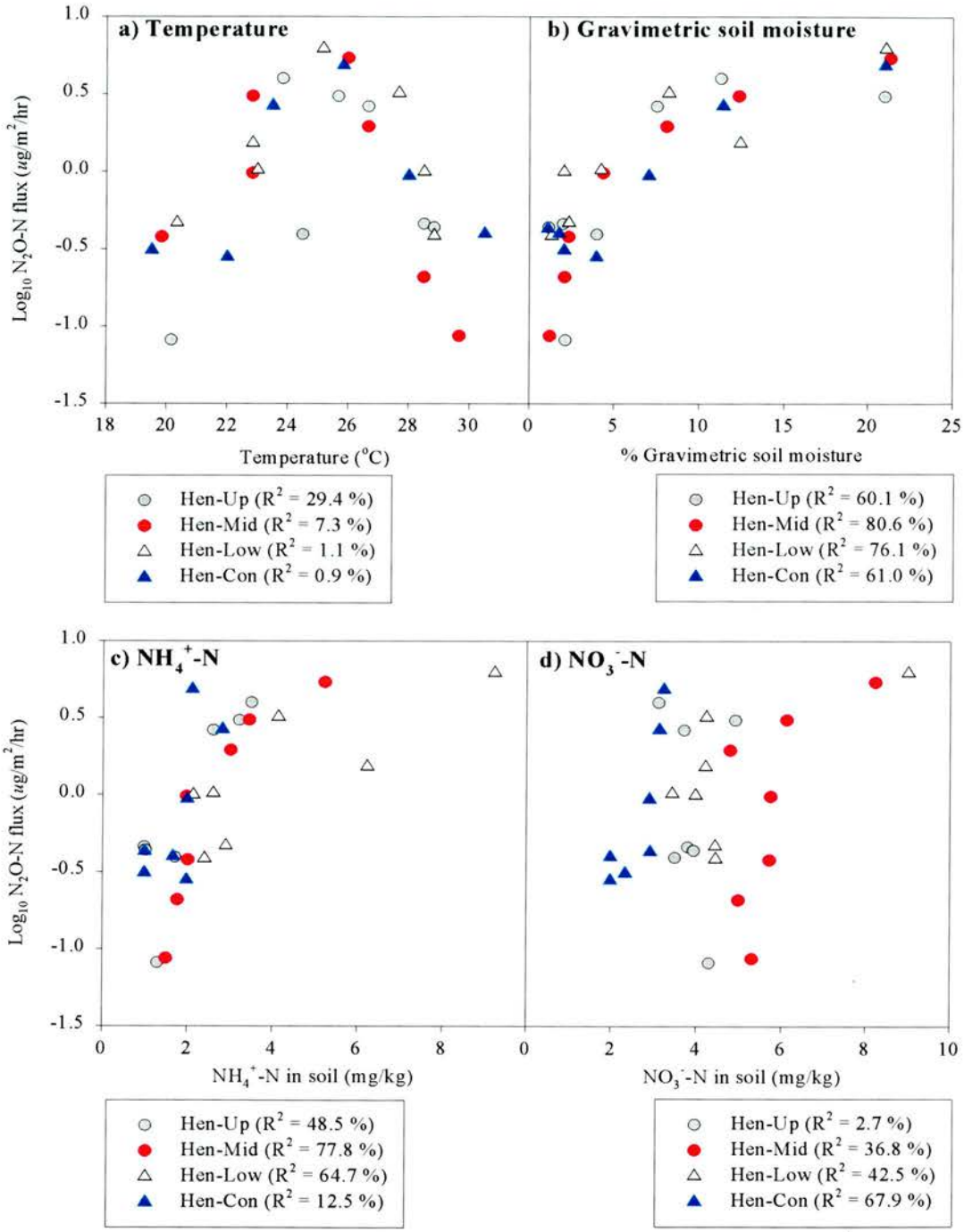


Figure 8.16. Relationship between nitrous oxide fluxes (without log-transformation) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and NO_3^--N (mg/kg) at Hen-Up, Hen-Mid, Hen-Low and Hen-Con during the dry season from April 2001 to September 2001. At all experimental sites, there was a positive linear relationship between N_2O emissions and soil moisture; $R^2 > 60$ %.



8.17. Relationship between nitrous oxide fluxes (log-transformed) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and d) NO_3^--N (mg/kg) at Hen-Up, Hen-Mid, Hen-Low and Hen-Con during the rain season from October 2000 to March 2001. No clear linear relationship was observed.



8.18. Relationship between nitrous oxide fluxes (log-transformed) and a) temperature (°C), b) gravimetric soil moisture (%), c) NH_4^+-N (mg/kg) and d) NO_3^--N (mg/kg) at Hen-Up, Hen-Mid, Hen-Low and Hen-Con during the dry season from April 2001 to September 2001. At all experiment areas there was a positive linear relationship between N_2O emissions and soil moisture; R^2>60.

At Mukuvisi Woodlands, Muk-Grass had the highest fluxes of N_2O-N because this experimental area also occupies the upper lower slope topographic position where in some rain seasons there is a high fluctuating water table. Denitrification is therefore higher than the other Mukuvisi sites. Muk-Prot is protected from burning and has higher litter inputs and N_2O-N gaseous loss compared to Muk-Burn. This could be due to higher mineral N from the litter and easily oxidisable C from the fresh litter. At Muk-Burn it is possible that some of the mineral N from the litter and easily oxidisable C was lost through burning. Measurements elsewhere found microbial cycling of N to be enhanced after fires. Crutzen and Andreae (1990) report higher NO and N_2O emissions from burnt than unburnt temperate experimental sites. They however point out that disturbed, that is, deforested and/or burnt tropical ecosystems may initially emit more N_2O, this may only be temporary and in the long term, less N_2O may be emitted. It may be possible that this is the case at Muk-Burn. Burning and clearing might not always result in increased N gaseous losses. Other workers have observed no significant change in N_2O fluxes on sites that were burned (Hao *et al.*, 1988; Luizão *et al.*, 1989). At Muk-Def it appears that clearing has resulted in less emissions of N_2O-N. Of the woodland areas at Mukuvisi Woodlands and Henderson Research Station study sites, experimental areas Hen-Low and Muk-Prot that had highest litter inputs had the highest N_2O-N lost. This is supported by the comparatively higher mineral N at Muk-Prot and Hen-Low which promote higher emissions (Mogge *et al.*, 1998).

Other workers have observed that sites that are more fertile with higher levels of N, or receive a fertilizer N input, lose more N through gaseous emissions (Keller *et al.*, 1988; Skiba *et al.*, 1993; Hall and Matson, 1999; Baggs *et al.*, 2000). In the other experimental areas there were lower litter inputs and lower mineral N, which could explain the lower N_2O-N losses. The N_2O-N losses were very low compared to N inputs in throughfall and litter (Table 8.2). N_2O-N losses from the experimental areas expressed as a percentage of the sum total of N additions in throughfall and litter was found to be less than 1 %. The order of the % N_2O-N lost from the highest to the lowest was Muk-Grass (0.70) > Hen-Con (0.41) > Muk-Def (0.37) > Muk-Con (0.33) > Hen-Low (0.11) > Hen-Mid (0.09) > Muk-Burn (0.08) > Muk-Prot (0.06) > Hen-Up (0.05).

8.5. OVERVIEW

Miombo woodlands lose N through gaseous emissions. N_2O fluxes were found to increase with the onset of the rainy season. This can be explained by the increase in moisture content and mineral N in the soil. N lost through emission of N_2O was, however, found to be very low (< 1 %) compared to the total nutrient additions in throughfall and litter. Though N_2O fluxes were the only emissions measured, N is also lost from this ecosystem as NO (Meixner *et al.*, 1997) and N_2. Measurements of these losses need to be made in order to understand fully gaseous N losses from this ecosystem.

Despite the low amount of N_2O-N losses in relation to N cycling in miombo woodlands, the amounts measured may contribute significant amounts to the atmosphere because these woodlands occupy a large area in Africa.

The low N_2O-N losses possibly indicate that nutrient cycling in miombo woodlands is tight. Compared to the area protected from burning one can conclude that these ecosystems are well adapted to fires. However, clearing of vegetation may have adverse effect on the geochemical cycling of nutrients especially N.

9. DISCUSSION AND CONCLUSION

9.1. NUTRIENT DYNAMICS

9.1.1. Nutrient cycling in miombo woodlands

The aim of this study was to measure inputs, outputs and internal cycling of nutrients in miombo woodlands so as to understand the nutrient dynamics and to assess the extent to which the miombo cycles nutrients efficiently. The study also sought to determine the effect of fire on nutrient dynamics. The components measured in this study at each experimental area during the 2000/2001 rainy season are presented in Figures 1 to 5.

Miombo woodlands like all ecosystems are open systems with nutrient inputs entering and outputs leaving and they are linked to the larger global system. Nutrients are cycled continuously within the woodland (Bruijnzeel, 1991) and can be divided into rapid cycling which involves throughfall, stem flow and fine litter fall and relatively slower cycling involving large woody plant parts (Edwards, 1982; Proctor, 1987; Figure 4.1). In this study cycling of nutrients in large woody plant parts was not measured. Rainfall was found to be an important input of nutrients to miombo woodlands especially nitrogen. Mineral N added to the Henderson Research Station woodlands in rainfall was 12.3 kg/ha/yr during the 1999/2000 rainy season. In the following 2000/2001 season, less rainfall was received and additions were 5.7 kg/ha/yr (Figure 9.3-5) almost half the amount received the previous season. Inputs at Mukuvisi Woodlands in rainfall were 14.7 kg/ha/yr and 7.4 kg/ha/yr (Figure 9.1 & 9.2) for the 1999/2000 and 2000/2001 rainy seasons respectively. These are comparable to inputs of 13 kg/ha/yr found by Nye (1961) in a forest in Ghana receiving 1850 mm rainfall per annum. However the Ghanaian site received almost double the amount of rainfall as the Zimbabwean study sites. Hendry *et al.*, (1984) found mineral additions amounting to 2.2 kg/ha/yr in a dry semi-deciduous forest in Costa Rica and Bruijnzeel (1989) 9.3 kg/ha/yr in a Java rainforest. Tropical rain forests, which receive at least 3 times the amount of rainfall as the study sites, might be expected to sustain greater throughfall and leaching; despite

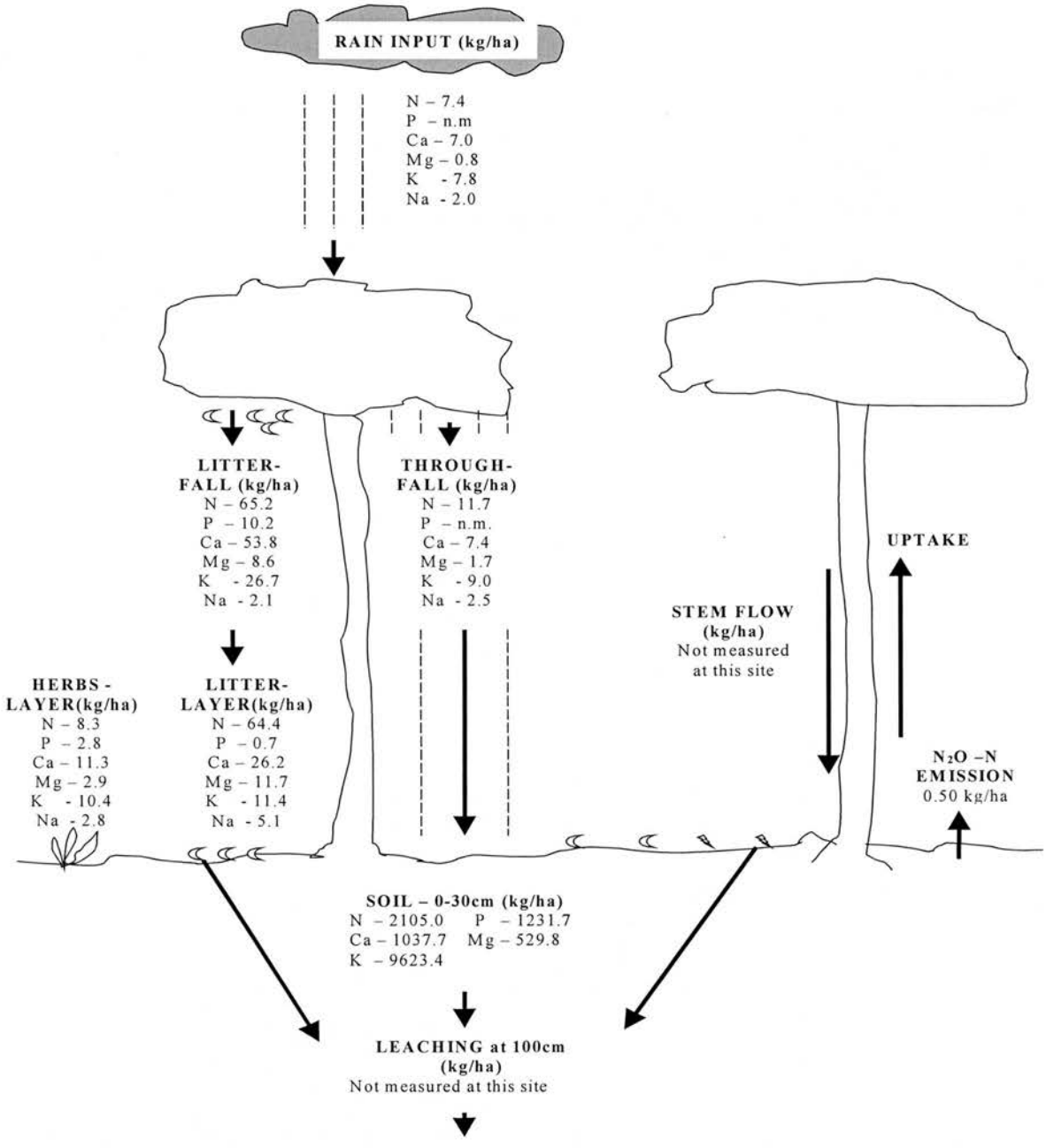


Figure 9.1. Summary diagram of nutrient cycling in Muk-Prot miombo woodland (the protected Mukuvisi woodland site) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Neither leaching nor stem flow measurements were carried out in this experimental area.

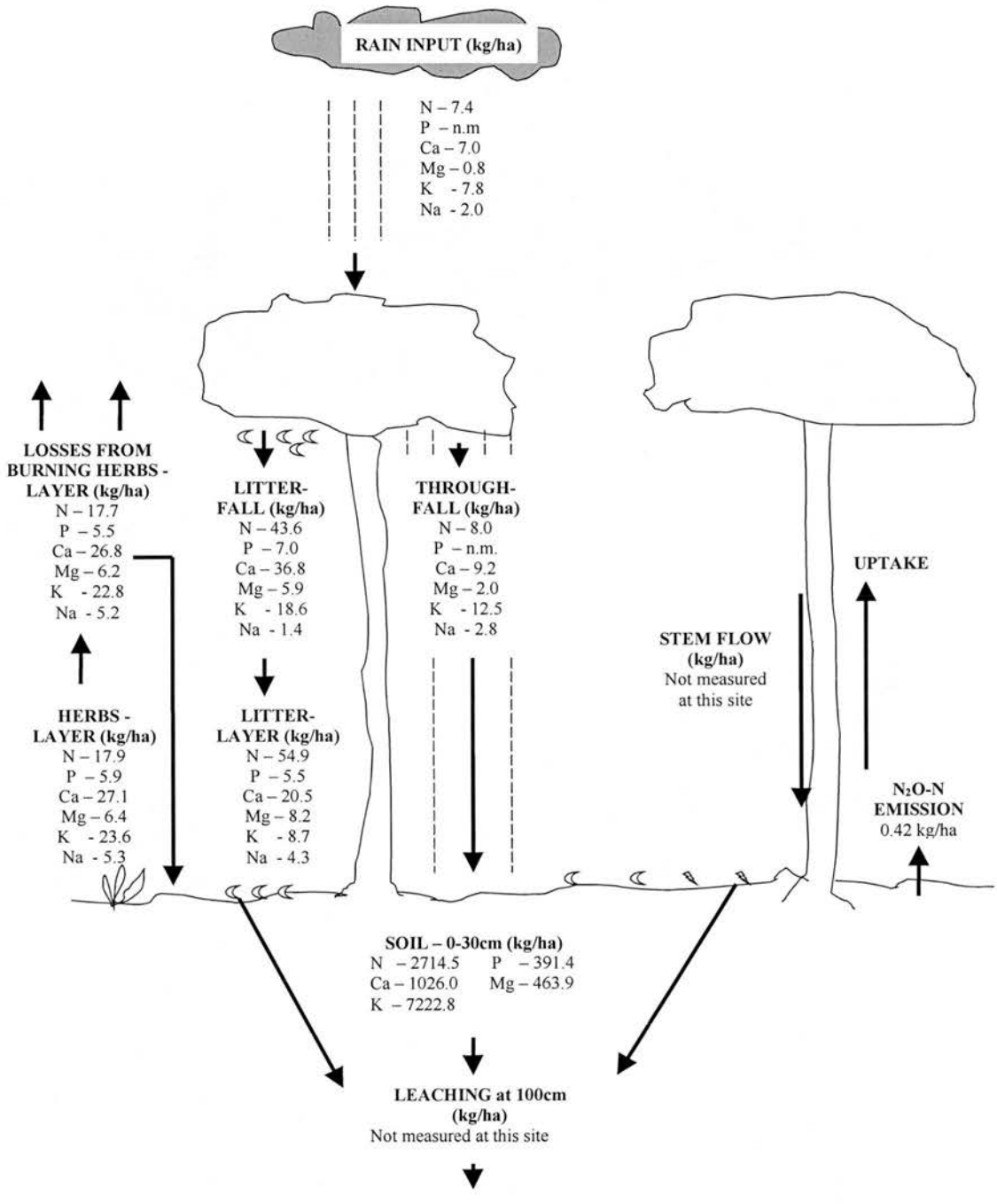


Figure 9.2. Summary diagram of nutrient cycling at Muk-Burn miombo woodland (the burnt Mukuvisi woodland site) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Neither leaching nor stem flow measurements were carried out in this experimental area.

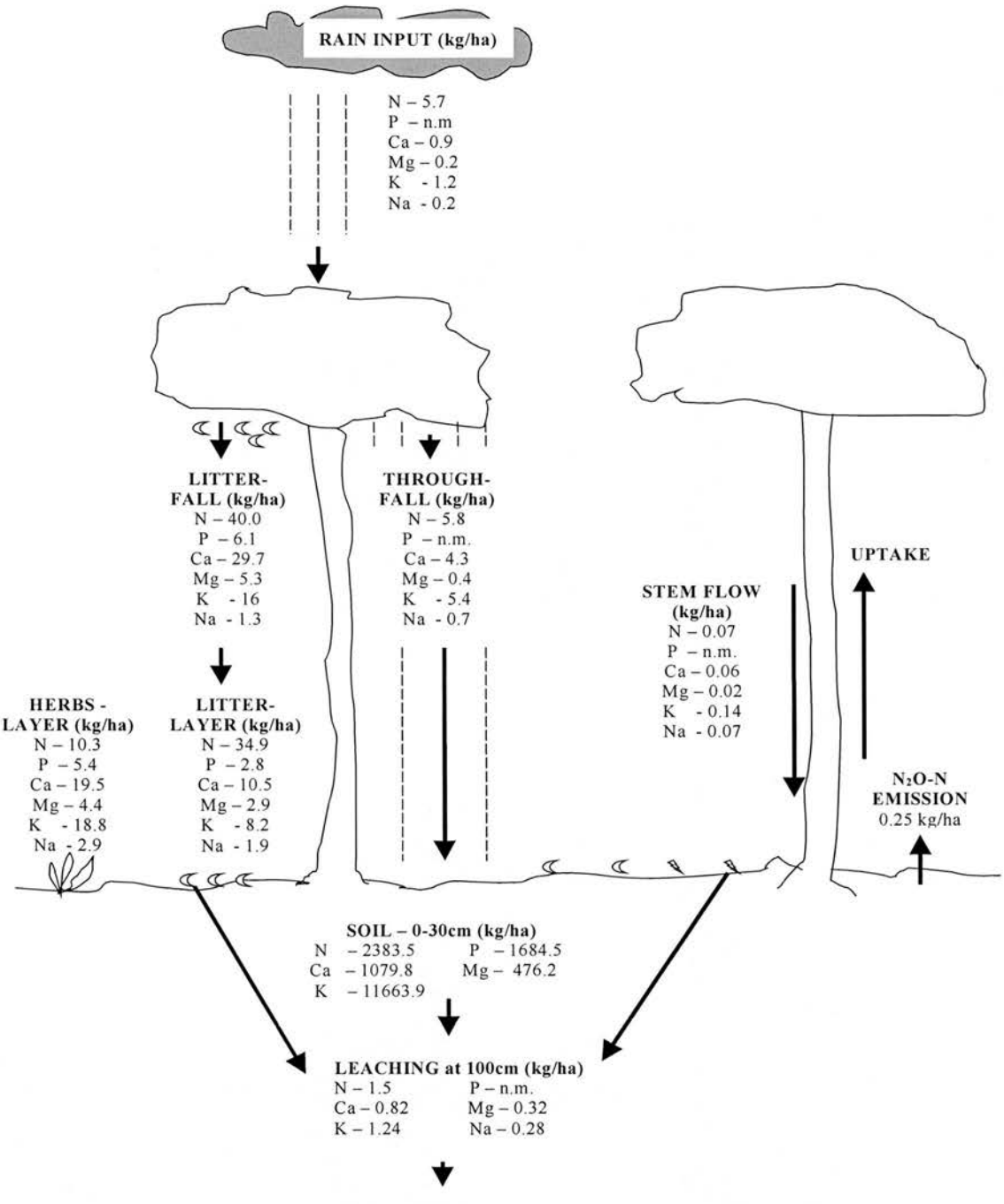


Figure 9.3. Summary diagram of nutrient cycling at Hen-Up miombo woodland (the higher section of the catena at Henderson) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Leaching and stem flow measurements were carried out in this experimental area. Leaching measurements presented were carried out at a depth of 100 cm.

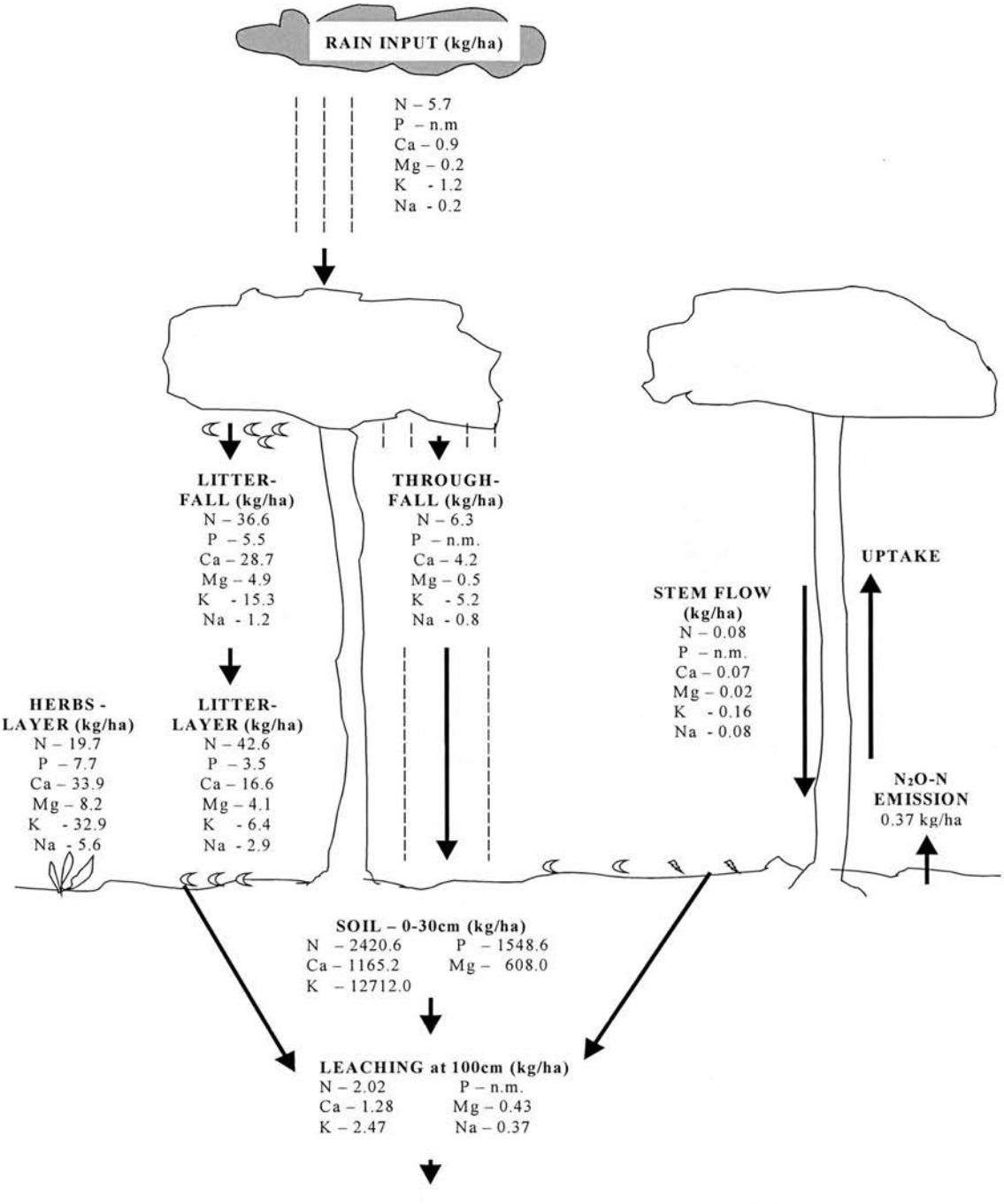


Figure 9.4. Summary diagram of nutrient cycling in Hen-Mid miombo woodland (the midslope section of the catena at Henderson) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Leaching and stem flow measurements were carried out in this experimental area. Leaching measurements presented were carried out at a depth of 100 cm.

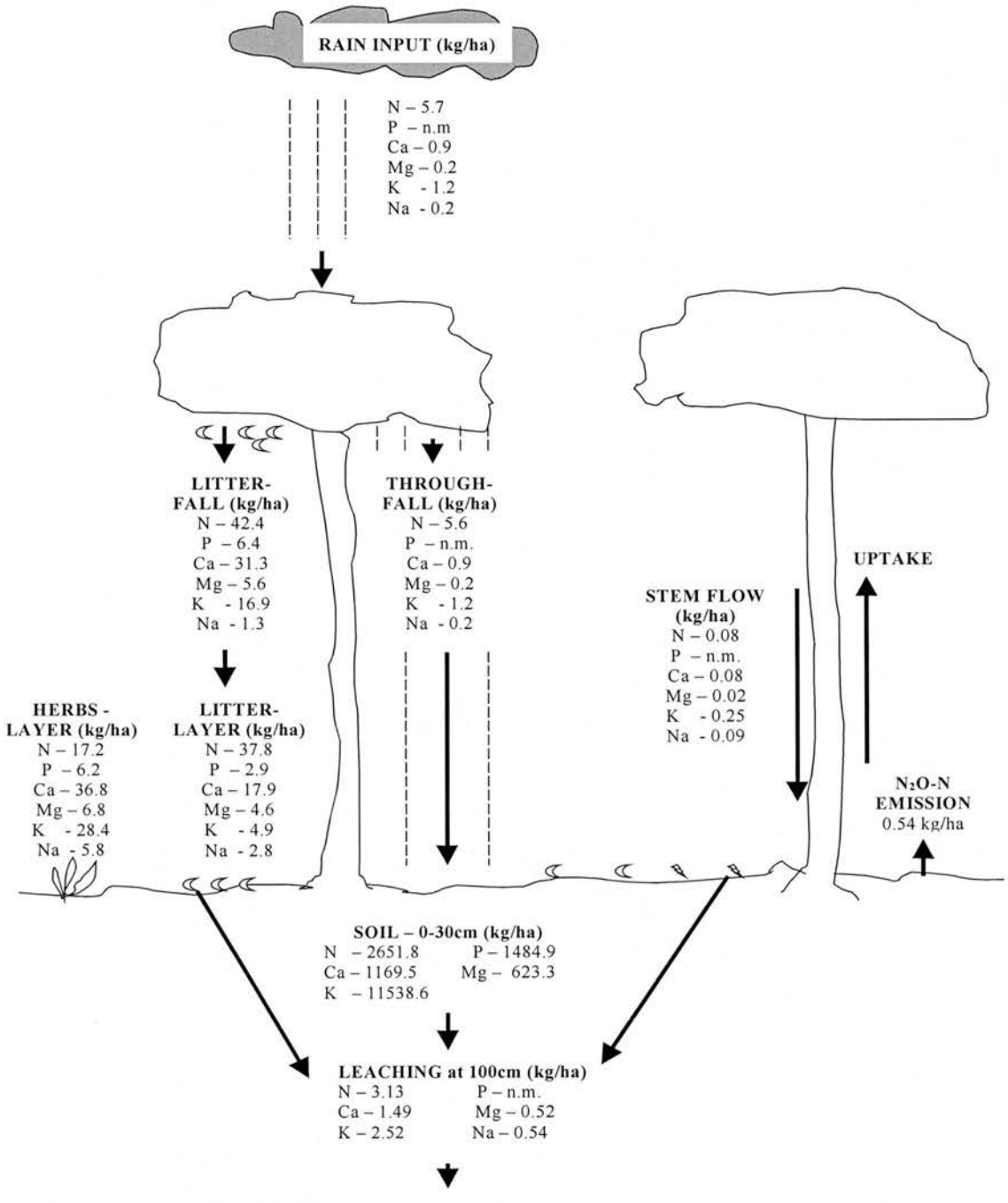


Figure 9.5. Summary diagram of nutrient cycling in Hen-Low miombo woodland (the lower section of the catena at Henderson) from October 2000 to September 2001. Nutrient quantities shown in the diagram are amounts transferred in kg/ha/year. Litterfall transfers a large proportion of nutrients to the woodland floor. The quantity of nutrients in leaves and woody parts was not be determined because it was not possible to carry out destructive sampling in the study areas. Leaching and stem flow measurements were carried out in this experimental area. Leaching measurements presented were carried out at a depth of 100 cm.

the seasonal nature of rainfall in central Zimbabwe, the total rainfall nutrient input is nevertheless high. Inputs of bases Ca, Mg, K and Na at Henderson Research Station were however, found to be lower than other tropical sites (Nye, 1961; Brassel and Gilmour, 1980; Hendry *et al.*, 1984; Bruijnzeel, 1989; Sinun *et al.*, 1992).

After passing through the canopy mineral N in rainfall was lowered during the 1999/2000 rainy season whilst on the other hand the bases increased significantly indicating the importance of the canopy as a source of bases to the woodland soil. These results are in agreement with research in other forest types which has shown that the canopy is an important source of bases (Edwards, 1982; Sinun *et al.*, 1992). It is likely that N was absorbed by leaves or adsorbed on plant surfaces (Proctor, 1987). The amount of bases in rainfall during the 2000/2001 rainy season also increased after passing through the canopy. N however showed no change and in some cases increased after rainfall passed through the canopy. Nutrient inputs and outputs into forest ecosystems are known to vary from year to year because no system is in a perfect steady state (Jordan, 1982). Edwards (1982) reports that N is difficult to leach from leaves and attributes the N increase in throughfall to biological fixation either in the canopy or the rain gauges. It is possible that some N is from within tree leaves, some from dry deposition, and some might be biologically fixed. Identification of the processes responsible for N enrichment in throughfall will require carefully designed and controlled experiments.

Potassium was the most abundant cation derived from the canopy and cation transfers were in the order K > Ca > Mg > Na at both Mukuvisi Woodlands and Henderson Research Station. In several studies elsewhere it has been observed that the forest canopy is an important source of bases to the forest floor, with K usually being the highest cation in throughfall (Eaton *et al.*, 1973; Bernhard-Reversat, 1975). Besides throughfall, litterfall can be seen to represent another important internal nutrient cycling pathway.

The total amount of litter transferred to the woodland floor at Mukuvisi Woodlands ranged from 3.0 to 4.4 t/ha/yr and at Henderson Research Station from 2.2 to 2.4 t/ha/yr. It is recommended that litter measurement should be carried out over a period of 3 years (Proctor, 1983), but in this study it was only possible to measure litterfall over 1 year. Litterfall is the largest nutrient cycling pathway in miombo woodlands, transferring between 36.6 to 65.2 kg N/ha/yr; 5.5 to 10.2 kg P/ha/yr; 15.3 to 26.7 kg K/ha/yr; 28.7 to 53.8 kg Ca/ha/yr; 4.9 to 8.6 kg Mg/ha/yr and 1.2 to 2.1 kg Na/ha/yr to the woodland floor in fine litter. The nutrient with the highest amount transferred in fine litter was N, whilst amongst cations Ca had the highest amount transferred to the woodland floor in fine litter. Many studies of litterfall in tropical forests have reported a high Ca return in fine litter (e.g. Vitousek, 1984). Before leaf fall, some nutrients are conserved by trees by re-absorbing them from senescing leaves. Results obtained seem to indicate that the most limiting nutrient on the basis of percent nutrient withdrawn is P. Phosphorus withdrawn ranged from 48 to 75 % of the total P in leaves of all the dominant miombo tree species. Nitrogen appeared to be the second most limiting nutrient and 22 to 33 % was withdrawn from all the dominant miombo tree leaves. A similar proportion of K was withdrawn ranging from 22 to 31 %. Withdrawal of Mg was from 12 to 21 %. The bases Ca and Na increased as the leaves matured. Re-absorption of nutrients is an important process in most ecosystems employed by plants to conserve nutrients (Killingbeck, 1996). In this study nutrient changes were determined over one season. There is however a possibility of variation of nutrients withdrawn from leaves depending on season and on among other factors the amount of rainfall received and length of the rain season (Killingbeck, 1996). A number of workers have found no clear relationship between the soil fertility of a site and the amount of nutrient re-absorbed or withdrawn (Aerts, 1996) and high re-absorption rates have been found on some high fertility sites (Birk and Vitousek, 1986; Chapin and Moilanen, 1991). Further studies particularly longer term experiments are therefore essential for understanding factors controlling nutrient withdrawal from miombo trees. It has been suggested that understanding the biochemistry involved in nutrient re-absorption might contribute towards a better explanation (Aerts, 1996).

Shed litter on the woodland floor releases nutrients through decomposition. After about 10 months, the remaining nutrients in litter as a percentage of initial amount was 10.1 to 69.2 % Ca; 10.3 to 66.2 % P; 7.9 to 49.6 % Mg; 4.1 to 21.4 % Na and 3.5 to 19.3 % K. Potassium was the most easily leached nutrient from litter and it was also found to be the most abundant cation in leachate collected from 100 cm depth. Though K occurs in high amounts it is susceptible to loss through leaching. This could be the reason why miombo trees withdraw a large percentage of K from leaves at senescence.

Nutrients leached from miombo soils were in the order K (1.24-2.52 kg/ha/yr) > NO_3^--N (1.11-2.30 kg/ha/yr) > Ca (0.82-1.49 kg/ha/yr) > NH_4^+-N (0.39-0.83 kg/ha/yr) > Na (0.28-0.54 kg/ha/yr) ≈ Mg (0.32-0.52 kg/ha/yr). Nitrogen is lost at 100 cm depth predominantly as NO_3^--N because it is not held on cation exchange sites. Though leaching was measured at a shallow depth of 100 cm in a woodland where tree roots can go as deep as 5 m (Chidumayo, 1993) measurements give an indication of how much was lost from within 100 cm and which nutrients are likely to be lost in significant amounts. Nutrients lost through leaching are likely to be derived from decomposition of litter and throughfall.

Other losses are from burning of miombo woodlands. Annual early burning at Muk-Burn resulted in loss of nutrients mainly from standing herbaceous plant material. N was the only nutrient observed to have been lost from litter in significant amounts after a fire confirming reports by other workers that N is easily lost through volatilisation (Frost and Robertson, 1987). Fire resulted in an immediate increase in % total organic C and P in top soils. Other nutrients Ca, K, Mg and Na appeared not to be affected immediately by early burning in miombo woodlands. However, results of burning over 13 years seem to suggest a significant decline in nutrients P, Mg and K in the burnt area. The other nutrients N and Ca seemed not to be affected by fire in the long term. Fire occurs regularly in miombo woodlands (Trapnell, 1959; Kikula, 1986) with a mean return interval of 1 to 4 years. Absence of fire in these ecosystems is rare (Frost and Robertson, 1987).

Losses of N in the form of N_2O were also measured and losses were found to range from 0.25 to 0.52 kg/ha/yr and 0.24 to 0.54 kg/ha/yr at Mukuvisi Woodlands and Henderson Research Station experimental areas respectively. Compared to nutrient additions, losses through this pathway are low. Miombo woodlands, however, occupy a large area in central and southern Africa and therefore, these emissions have a significant effect on levels of greenhouse gases (Scholes, 1996). If the Henderson experimental sites (emitting a mean of 0.39 kg N_2O-N /ha/yr) are taken as typical of miombo woodlands, it is estimated that miombo woodlands which occupy 2.7 million km^2 (Millington *et al.*, 1994) will emit 0.11 Tg N_2O-N per year.

9.1.2. Comparison of inputs and losses

The main sources of nutrients added to miombo woodlands are incident rainfall, throughfall and stem flow. Throughfall and stem flow contain nutrients from incident precipitation and any nutrients picked up from the canopy which may have originated from dry deposition on tree surfaces or from within the leaves.

Comparison of the nutrient inputs with losses can give an indication of whether the system is gaining or losing nutrients. At Henderson Research Station study sites, leaching and N_2O-N losses were measured (Figure 9.3-5) and at Mukuvisi Woodlands only N_2O-N emissions and losses through burning (at Muk-Burn) were measured. At Henderson Research Station study sites, the woodlands appear to be gaining nutrients when inputs in throughfall and stemflow are compared to leaching and N_2O-N emission, though some of the nutrients in throughfall and stemflow are part of within woodland or internal nutrient cycling. When compared with inputs in rainfall the bases in leachate at 100 cm are similar or higher than rainfall inputs. This might appear as if leaching losses are higher than rainfall nutrient inputs; leaching was only measured at 100 cm depth and miombo tree roots can grow to about 5 times as deep. Deeper roots may take up more nutrients from the leachate so reducing the quantity of nutrients likely to be lost from the system through leaching. It is therefore likely that leaching losses are low. Jordan (1982) also reports rates of leaching lower or equal to inputs from the atmosphere. Nitrogen was however found to be higher in rainfall than in leachate and a

large proportion is taken up by miombo vegetation. This, coupled with N withdrawal from senescing leaves suggests that N is cycled efficiently in these ecosystems.

At Mukuvisi Woodlands study sites, no leaching measurements were made, only N_2O-N emission and losses through burning (Muk-Burn) were measured (Figure 9.1 &2). Though leaching losses were not measured, it is likely that losses are higher at this site than at Henderson Research Station experimental areas because of the coarse sandy texture of the underlying soils. Losses from burning herbaceous vegetation are indicated in Figure 9.2 and are very high, though some may be transferred to the soil during the fire. Burning therefore is a major nutrient loss from the miombo woodlands.

Losses may also be found through overland flow and lateral subsurface flow especially within 50 cm depth. These components were however not measured in the present research. Though N_2O-N emission is about a sixth of mineral N lost through leaching at 100 cm depth, it is likely that when all N gas losses are accounted for, that is, N_2O, NO and N_2, gaseous emission may be comparable or even higher than N leached out from the system.

9.1.3. Comparison of nutrients in soil and litter

The amount of nutrients in the top 30 cm of soil was found to be many times higher (Figure 9.1-5) than nutrients transferred in litter as observed by other workers (Edwards, 1982; Edwards and Grubb, 1982). The nutrient reservoir in soils seem to indicate that nutrients are abundant and therefore miombo woodlands are not nutrient limited. It is however likely that a very large proportion of the soil nutrients is not readily available, the bulk being fixed in organic matter (Edwards, 1982). Possible evidence of limited availability, especially of nutrients P, N and K for plant use is the withdrawal of these nutrients by the trees at senescence. Miombo woodland systems seem to be gaining nutrients from rainfall, throughfall and stem flow. Some of the nutrients gained are likely to form part of the nutrient stock of the woodlands because at both study sites the number of small and young trees is high (Jordan, 1982). As the young trees grow more nutrients gained become part of the standing stock. Some the nutrients gained may,

however be lost through burning as at Muk-Burn. Nutrients can also be lost through other pathways such as overland flow, erosion, herbivory and subsurface throughflow, components not measured in this study. Sinun *et al.*, (1992) reports that a very high quantity of nutrients are transferred in subsurface throughflow.

9.1.4. Implications on land use and management

Observations at the woodland burnt site (Muk-Burnt) show that early burning has negative effects on the vegetation. It has the effect of preventing small trees from maturing. In view of this, it is suggested that burning should be carried out after a longer time interval to allow smaller trees to mature and become resistant to fire. This could be achieved by rotating the area burnt annually so that the whole Muk-Burn is not burnt every year. Such a rotation will however need to ensure that the protected woodland remains protected from fire. Early fires also result in some loss of nutrients especially N. Nutrient inputs however, appear to be adequate to offset this loss.

The protected woodland area (Muk-Prot) has been protected from fire for over 10 years. Such a situation results in accumulation of fuel increasing the risk of accidental intensive fires (Gillon 1983) as was the case at the Henderson Research Station experimental areas, where almost all the litter and herbaceous vegetation was destroyed in October, 1999. Destruction of the litter should be avoided because, as has been shown in this research, a large proportion of nutrients are cycled through litter. It is therefore recommended that the amount of fuel accumulating in the Mukuvisi protected woodland area (Muk-Prot) be reduced in order to avoid a destructive fire.

9.2. AREAS OF FURTHER RESEARCH AND IMPROVEMENTS

It was observed during the course of this study that some of the methodologies used could be improved and suggested improvements are outlined below. There are also some gaps in knowledge that need further research work. One such area is the total quantity of nutrients in leaves and woody plant parts which was not determined because it was not possible to carry out destructive sampling in the study areas. Determining the

nutrient stocks in woody plants is essential in understanding nutrient cycling in forestry ecosystems. Other areas requiring further research where also identified and some are discussed below.

9.2.1. Throughfall

The rain gauges used in the study were covered with funnels with large holes that allowed some debris and insects to fall into the water. Use of rain gauges with funnels with finer mesh could have prevented or reduced the amount plant debris, bird droppings and/or insect frass from going into the water. Rain collectors kept in the field may also collect aerosols, Jordan (1982) suggests exposing collectors only during storms. This can however result in logistical problems that can lead to missing rainfall events. Measurement of dry deposition and subtracting this input from throughfall is an alternative. Dry deposition was not measured. Its contribution to nutrient cycling in miombo woodlands needs to be assessed. In this study it was assumed that nutrients deposited were washed-off from plant surfaces by precipitation and measured either in throughfall and/or stem flow. However dry deposition that falls directly onto the forest floor was not measured. This input needs to be measured separately and it might be higher on open sites.

Nutrients may also be added in organic form. Other researchers (Carlisle *et al.*, 1967) observed that nutrients especially N and P could be added to the soil in throughfall and stemflow in organic form. In this study, it was assumed that the bulk of additions are in mineral form and therefore only mineral forms were measured.

Chemical analyses of nutrients in rainfall and throughfall water samples were carried out on volume-weighted monthly composite samples. It would have been preferable to make analyses for each rainfall event in order to see the variability in nutrient contents. However, this was not possible because of constraints in logistics and resources.

Not all the water that passes through the canopy to reach ground level, ends up in the soil. Measurement of run-off or overland flow and amount of nutrients lost through this pathway is also important in forest nutrient cycling. Litter and plant debris can be

moved by overland flow, this may need to assessed, especially at the Henderson Research Station experimental areas where there was appreciable slope. The water that enters the soil may also be lost through deep seepage and sub-surface throughflow.

It would be useful to have a longer period of observation and measurement, of not less than 3 years, so as to capture the pattern and variation of nutrient transfers in rainwater passing through miombo woodlands.

9.2.2. Fire and termites

Fire and termites in miombo woodlands have complementary effects. Fire results in removal of herbaceous plants and some litter and immediate release of nutrients whereas termites consume some litter and herbaceous plants and incorporate some in their mounds which is believed to be slowly available to woodland vegetation (Jones, 1990).

Termites are common in miombo woodlands in central and southern Africa (Dangerfield, 1990) and other tropical forest and savanna regions (Jones, 1990; Howse, 1992) where they play an important role in nutrient cycling. The type of termite species and effect of termite mounds on soil nutrients in Zimbabwe and other tropical regions is well documented (Watson, 1964, 1976 & 1977; Trapnell *et al.*, 1976; Dangerfield, 1990; Jones, 1990; Stromgaard, 1990; Abbadie *et al.*, 1992; Lavelle *et al.*, 1994). Limited work has, however been carried out on effect of mound building and non-mound building termites on miombo vegetation and nutrient cycling (Malaisse, 1976; Abbadie *et al.*, 1992). A study of the effect of termites on structure and functioning of the woodlands through feeding and mound building activities and the availability of nutrients locked up in mounds in miombo woodlands is essential to understand their ecology and influence on plants. In the present study it was observed that termites consume large amounts of litter, and this is likely to have a significant effect on nutrient cycling in miombo woodlands because the largest proportion of nutrients are cycled in litter.

Like termites, fire consumes woodland litter and herbaceous plants. In the present study the effect of fire on nutrient cycling in miombo woodlands was studied on an area that has been subjected to burning for only about 13 years. One weakness of this study is that the sites that were selected on burned areas and adjacent unburned areas were used for comparison on the assumption that they were similar before the fire (DeBano and Conrad, 1978). This is unproven though it is believed that the sites were similar. Experiments are needed where initial soil and vegetation conditions including litter are characterised and changes monitored over many years because fire experiments are long term (Trapnell *et al.*, 1976). In such experiments, fire must be adequately described, that is, its temperature, intensity and duration measured. Fire is also a source of greenhouse gases (Scholes, 1996) and therefore fire experiments should include measurements of greenhouse gases.

9.2.3. N gaseous emissions

Results from this study show that N_2O emissions from miombo woodlands are low but because they occupy a large area in central and southern Africa the emissions have a significant effect on levels of greenhouse gases (Scholes, 1996). Measurement of N_2O emissions alone is not sufficient to give a full picture of N gas emissions. N can be lost as NO, N_2 and NH_3 which were not measured in this study. It is possible that a significant amount of N was lost in these forms. A study that accounts for all the gaseous emissions is essential and understanding trace gas production requires identification of processes responsible and the factors that control these processes. Such a study would require the inhibition of the formation of N_2 using acetylene (Mosier, 1990) and also quantify NH_3 volatilisation (Proctor, 1987).

The results obtained are useful for making estimates of N cycling and potential N_2O contribution to the atmosphere. These estimates can be improved by using a large number of static chambers to measure N fluxes so as to capture spatial variation of gaseous N emissions within miombo woodlands. In order to establish a sound pattern of gas fluxes, it would be helpful to establish long-term measurements that account for all N gaseous emissions from miombo woodlands.

9.3. CONCLUSION

The results from this study seem to indicate that miombo woodlands cycle nutrients efficiently. The internal nutrient cycling comprising mainly litterfall recycle the largest proportion of nutrients. Losses through gaseous N emissions are low as indicated by N_2O emission measurements. Leaching losses relative to the sum of throughfall and stem flow were also found to be low. Fire resulted in some nutrient losses confirming the hypothesis that burning miombo woodlands results in loss of nutrients.

The general conclusions that can be drawn from this study are therefore, that:

i) Early fires prevent smaller trees from maturing and growing. They result in the loss of nutrients N, P, Ca, Mg, K and Na from herbaceous vegetation; from litter only N is lost in significant amounts.

ii) Rainfall is an important source of N and throughfall is an important source of basic cations Ca, Mg, K and Na.

iii) Dominant miombo woody tree species conserve nutrients by withdrawing P, N and K from senescing leaves.

iv) The largest proportion of nutrients is recycled in litterfall.

v) K and Na are released fastest from decomposing litter compared to other nutrients.

vi) Gaseous N losses may be similar or even higher than losses through leaching.

Though many gaps still exist in our knowledge of miombo nutrient cycling, this study has provided new and important data on nutrients in rainfall, throughfall, stemflow and

N_2O-N emission. A number of areas outlined in section 9.3 however, need to be followed up over a long time period of not less than 3 years to broaden our understanding of nutrient dynamics in miombo woodlands and establish trends and seasonal variations.

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11. APPENDICES

APPENDIX 1. HERBACEOUS BIOMASS (g/m^2) AND SPECIES COMPOSITION IN THE EXPERIMENT SITES AT MUKUVISI WOODLANDS AND HENDERSON RESEARCH STATION.

SPECIES	MUK-PROT	MUK-BURN	MUK - GRASS	MUK-DEF	HEN-UP	HEN-MID	HEN-LOW
Achyranthes aspera	0.392	0.000	0.000	0.000	0.000	0.000	0.000
Ageratum conyzoides	0.231	0.000	0.165	0.000	1.277	0.000	0.000
Andropogon gayanus	0.579	0.000	0.000	0.000	0.000	0.000	0.000
Anthospermum ternatum	0.611	0.000	0.000	0.000	0.000	0.000	0.000
Aristida meridionalis	0.777	0.000	0.000	0.000	0.000	0.000	0.000
Asparagus africanus	0.488	0.000	8.495	0.000	0.000	0.000	0.000
Bidens pilosa	1.222	0.000	0.000	0.000	0.000	0.178	0.307
Blumea crispata	0.000	0.000	0.000	0.000	0.913	8.587	0.142
Brachiaria brizantha	9.177	4.237	0.000	0.000	4.215	0.000	0.000
Chloridion cameronii	25.055	12.385	7.429	14.560	3.065	0.000	0.000
Commelina africana	1.098	0.000	0.000	0.000	0.000	0.000	0.000
Conyza sumatrensis	0.000	0.000	0.000	0.000	0.000	0.058	0.387
Crassocephalum rubens	0.069	0.000	0.000	0.000	0.373	0.000	0.698
Crotolaria bequaertii	0.181	0.000	0.000	0.000	0.000	0.000	0.000
Cynodon sp.	0.687	0.000	0.654	4.454	0.000	0.000	0.000
Cyperus sp.	0.000	0.000	0.000	0.000	0.028	3.378	0.115
Deloma anomala	0.469	0.000	0.000	0.000	0.000	0.000	0.000
Desmodium uncinatum	0.000	0.000	0.000	0.000	6.945	0.000	1.350
Eragrotis chapelieri	1.298	0.000	7.706	1.724	0.000	0.000	0.000
Eragrotis curvula	0.200	10.489	0.000	4.764	0.822	0.000	0.000
Eragrotis sclerantha	8.534	9.889	0.000	0.000	13.792	19.855	0.000
Felicia muricata	0.205	0.000	0.133	0.000	0.000	0.000	0.000
Fimbristylis hispidula	1.131	8.168	0.000	5.318	1.455	13.522	0.580
Galinsoga parviflora	0.145	0.000	0.000	0.000	0.000	0.000	0.000
Gerbera sp.	0.105	0.000	0.000	0.000	0.308	0.000	0.000
Helichrysum candolleanum	0.114	0.000	0.000	0.000	0.000	0.000	0.000
Heteropogon contortus	7.702	7.565	0.000	3.258	1.593	1.237	21.545
Hyparrhenia filipendula	54.923	28.621	48.334	69.318	1.893	5.720	43.162

Hyparrhenia newtonii	0.000	0.000	0.000	0.000	23.728	0.000	0.000
Hyparrhenia rufa	0.000	0.000	0.000	29.346	0.000	1.742	0.270
Hyperthelia dissoluta	0.669	0.450	1.200	6.552	0.000	0.000	0.000
Justicia elegantula	0.000	0.000	0.000	0.572	0.000	0.000	0.000
Justicia phyllostachys	0.000	0.000	0.634	0.000	0.000	0.000	0.000
Kalanchoe lanceolata	0.171	0.000	0.000	0.000	0.000	0.000	0.000
Leucas martinicensis	0.167	0.000	0.000	0.000	0.000	0.000	0.000
Leucas nyassae	0.000	0.000	0.000	0.000	0.000	1.437	0.000
Melinis repens	3.552	10.426	0.645	13.622	0.000	0.000	0.000
Oldenlandia herbacea	0.586	0.000	0.000	0.000	0.000	0.000	0.000
Panicum repens	0.000	0.000	1.800	0.000	0.000	0.000	0.000
Perotis patens	0.000	0.000	1.073	0.000	0.000	0.000	0.000
Phyllanthus myrtaceus	0.361	0.000	0.000	0.000	0.000	0.000	0.000
Phyllanthus sp	0.138	0.000	0.000	0.000	0.000	0.000	0.000
Pogonarthria squarossa	7.704	0.276	9.242	9.656	0.000	0.000	0.000
Rhynchosia minima	1.024	0.000	0.000	0.000	0.000	0.000	0.000
Richardia scabra	0.000	0.000	1.457	0.000	0.000	0.000	0.000
Rynchelytrum nyassanum	2.982	11.655	0.000	0.000	0.910	5.887	0.000
Schizachyrium jeffreysii	9.969	16.363	8.409	0.000	4.147	20.852	0.000
Sesamum calycinum	0.000	0.000	0.268	0.000	0.000	0.000	0.000
Solanum incanum	0.332	0.000	0.000	0.000	0.000	0.000	0.000
Sporobolus pyramidalis	17.561	6.175	95.302	0.776	0.000	25.820	88.455
Tagetes minuta	3.402	0.000	0.000	0.000	0.000	0.000	0.000
Tephrosia micrantha	0.000	0.000	0.000	0.000	0.428	0.000	0.000
Themeda triandra	0.000	0.000	0.000	0.000	10.352	0.000	10.935
Thessium gracile	0.000	0.357	0.000	0.000	0.000	0.000	0.000
Thunbergia huillensis	0.000	0.000	0.000	0.000	1.397	0.000	0.000
Thunbergia lancifolia	0.121	0.000	0.000	0.000	1.660	0.000	0.000
Unknown herb-1	0.060	0.000	0.000	0.000	0.000	0.000	0.000
Unknown herb-2	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Venonia poskeana	0.040	0.000	0.000	0.000	0.945	0.430	0.000
Verbena bonariense	0.363	0.000	0.000	0.000	0.000	0.000	0.000
Vigna sp.	0.111	6.000	0.000	0.000	0.000	0.000	0.000
Wahlenbergia undulata	0.000	0.000	0.637	0.000	0.000	0.000	0.000
Zonia linearis	0.000	0.000	0.000	0.000	0.000	0.000	0.000

APPENDIX 2. Total stems (stems/ha) of all tree species in quadrats at Henderson Research Station and Mukuvisi Woodlands experiment sites

EXPERIMENT SITE	Mukuvisi Burnt Woodland				Mukuvisi Protected Woodland				Henderson Upperslope				Henderson Middleslope				Henderson Lowerslope			
SPECIES	0.5 ≥ 3 m	3 ≥ 6 m	6 ≥ 9 m	9 ≥ 15 m	≤ 3 m	3 ≥ 6 m	6 ≥ 9 m	9 ≥ 15 m	≤ 3 m	3 ≥ 6 m	6 ≥ 9 m	9 ≥ 15 m	≤ 3 m	3 ≥ 6 m	6 ≥ 9 m	9 ≥ 15 m	≤ 3 m	3 ≥ 6 m	6 ≥ 9 m	9 ≥ 15 m
Acacia spp.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	55	0	55	0
Brachystegia boehmii	0	0	0	0	0	0	0	0	196	102	47	102	165	291	110	55	341	629	110	115
Brachystegia spiciformis	324	31	38	49	510	177	66	0	149	51	248	51	170	55	340	222	110	166	292	166
Burkea africana	135	45	4	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Combretum apiculatum	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Combretum molle	51	11	6	0	0	0	0	0	51	0	0	0	2	0	0	0	0	0	0	0
Cussonia spp.	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dichrostachys cinerea	1	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
Erythrina abyssinica	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gardenia spp.	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0
Julbernadia globiflora	1427	65	64	0	1133	1100	200	0	196	349	149	0	115	519	226	60	0	0	0	0
Lannea discolour	33	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lantana camara	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Monotes glaber	155	51	0	16	0	55	66	0	0	0	0	0	0	60	0	0	0	0	0	0
Ozoroa reticulata	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parinari curatellifolia	26	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pseudolachnostylis maprounefollia	14	0	0	0	33	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pterocarpus angolensis	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Strychnos spinosa	25	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swartzia madagariensis	7	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Terminalia sericea	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uapaca kirkiana	54	60	0	0	0	33	100	0	0	98	0	0	0	0	0	0	0	0	0	0
Vangueria infausta	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vangueriopsis lanciflora	56	16	0	0	199	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0
Ximenia caffra	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
TOTAL STEMS/HA	2359	306	113	77	1976	1431	436	0	592	601	444	153	564	927	677	337	506	795	457	281

APPENDIX 3: PROFILE DESCRIPTIONS AND ANALYTICAL DATA

HENDERSON RESEARCH STATION PIT 1 – PROFILE DESCRIPTION

Location: Hen-Up experimental area
Site: Upper slope, pediment; 3-5 % slope
Vegetation: The dominant species are *B. spiciformis*, *J. globiflora*, *B. boehmii*, and a few *P. curatellifolia* and *U. kirkiana*.
Parent Material: Argillaceous metasediment
USDA Soil Classication: Haplustalf

Description:

0-10 cm:
Dark brown (7.5YR 5/4 dry, 3/4 moist) dry slightly hard gravelly loam. Weak, fine subangular blocky structure, numerous fine roots, well drained and good permeability. Clear smooth transition to:

10-20 cm:
Yellowish red (5YR 5/6 dry, 4/6 moist) dry slightly hard gravelly clay loam with numerous fine roots. Weak, fine subangular blocky structure, numerous fine roots, well drained and rapid permeability. Clear smooth transition to:

20-58 cm:
Very gravelly horizon with numerous quarzt stones and gravels. Very well drained and rapid permeability. Horizon not sampled for laboratory analysis. Diffuse boundary to:

58-150 cm:
Similar to above horizon, but with larger stones (> 10 cm). Horizon to base of pit.

HENDERSON RESEARCH STATION PIT 1 – ANALYTICAL DATA

DEPTH	0-10 cm	10-20 cm	20- 58
DM%	98.5	98.5	Not sampled
TEXTURE	Loam	Clay Loam	
CLAY %	19	36	
SILT %	35	28	
FINE SAND %	34	22	
MEDIUM SAND %	6	5	
COARSE SAND %	6	8	
pH (CaCl)	4.8	4.7	
Ex. Ca m.e.%	3.7	2.2	
Ex. Mg m.e.%	1.7	1.4	
Ex. Na m.e.%	0.03	0.03	
Ex. K m.e.%	0.34	0.39	
TEB m.e.%	5.8	4	
CEC m.e.%	7.43	6.3	
Base Saturation %	78	63	

HENDERSON RESEARCH STATION PIT 2 – PROFILE DESCRIPTION

Location: Hen-Mid experimental area
Site: Middle slope position on the catena, pediment; 1-2 % slope
Vegetation: The dominant species are *B. spiciformis*, *J. globiflora*, *B. boehmii*, and very few *B. africana*
Parent Material: Argillaceous metasediment mixed with colluvial material
USDA Soil Classication: Haplustalf

Description:

0-14 cm:
Dark brown (7.5YR 5/4 dry, 3/4 moist) dry hard clay loam with numerous fine and many coarse roots. Moderately well developed medium to coarse subangular blocky structure, well drained and with good permeability. Clear smooth transition to:

14-28 cm:
Yellowish red (5YR 5/6 dry, 4/6 moist) dry hard clay loam with numerous fine and many coarse roots. Moderately well developed medium to coarse subangular blocky structure, well drained and with good permeability. Clear smooth transition to:

28-60 cm:
Red (5YR 5/6 dry, 2.5YR 4/6 moist) dry hard clay loam with numerous fine and many coarse roots. Moderately well developed medium to coarse subangular blocky structure, well drained and with good permeability. Abrupt transition to:

60-70 cm:
Stoneline with large stones (< 10 cm), many fine and coarse roots, well drained with rapid permeability. Clear smooth transition to:

70-150 cm+:
Gravelly horizon with soft weathering parent material. Well drained with rapid permeability.

HENDERSON RESEARCH STATION PIT 2 – ANALYTICAL DATA

DEPTH	0-15 cm	15-52 cm
DM%	98.8	98.7
TEXTURE	Sandy clay loam	Clay loam
CLAY %	23	33
SILT %	31	29
FINE SAND %	33	29
MEDIUM SAND %	6	4
COARSE SAND %	8	4
pH (CaCl)	5.1	4.9
Ex. Ca m.e.%	3.3	2.5
Ex. Mg m.e.%	2.1	2.5
Ex. Na m.e.%	0.03	0.03
Ex. K m.e.%	0.29	0.25
TEB m.e.%	5.72	5.4
CEC m.e.%	7.4	7.5
Base Saturation %	77	72

HENDERSON RESEARCH STATION PIT 3 – PROFILE DESCRIPTION

Location: Hen-Low experimental area
Site: Lower slope position on the catena, pediment; approximately 1 % slope
Vegetation: The dominant species are *B. spiciformis* and *B. boehmii.*
Parent Material: Colluvial material
USDA Soil Classication: Haplustalf

Description:

0-18 cm:
Dark brown (10YR 5/3 dry, 3/3 moist) dry, very hard clay loam with numerous fine and medium roots. Moderately well developed coarse subangular blocky structure, well drained with good permeability. Clear transition to:

18-30 cm:
Strong brown (7.5YR 5/6 dry, 4/6 moist) dry, very hard clay loam with numerous fine and medium roots. Moderately to strongly well developed coarse subangular blocky structure, well drained with good permeability. Abrupt transition to:

30-60 cm:
Stoneline with many stones and gravels (< 10 cm) and soil similar to above horizon. Well drained and rapid permeability. Clear smooth transition to:

60-85 cm:
Yellowish red (5YR 4/4 dry, 4/6 moist) dry very hard clay with tongueing and faint mottling, few fine and coarse roots. Strongly developed coarse subangular blocky structure, moderately well drained and moderately restricted permeability. Clear smooth transition to:

85-140 cm+:
Variegated yellowish brown (10YR 5/4 dry, 5/6 moist) and strong brown (7.5YR 4/6 dry, 4/6 moist) dry very hard clay with few fine and coarse roots. Strongly developed coarse subangular blocky structure, moderately well to moderately poorly drained and moderately restricted permeability.

HENDERSON RESEARCH STATION PIT 3 – ANALYTICAL DATA

DEPTH	0-14 cm	14-28 cm	28-60 cm	60-85 cm	85-140 cm
DM%	98	98.1	98.3	97.3	97.3
TEXTURE	Clay loam	Clay loam	Clay	Clay	Clay
CLAY %	21	32	43	68	63
SILT %	36	31	30	19	22
FINE SAND %	33	26	18	11	11
MEDIUM SAND %	6	6	4	1	2
COARSE SAND %	5	5	6	2	2
pH (CaCl)	4.8	4.9	5	5	5.2
Ex. Ca m.e.%	3.2	3.1	3.6	5.8	4.8
Ex. Mg m.e.%	2.7	2.3	3.3	5.4	5.8
Ex. Na m.e.%	0.03	0.03	0.03	0.03	0.03
Ex. K m.e.%	0.35	0.26	0.25	0.21	0.14
TEB m.e.%	6.2	5.7	7.2	11.5	10.7
CEC m.e.%	9.4	8.7	9.3	12.9	13.1
Base Saturation %	66	65	78	89	82

MUKUVISI WOODLANDS PIT 1 – PROFILE DESCRIPTION

Location: Muk-Grass experimental area
Site: Lower middle slope position on the catena close to the vlei/dambo, pediment; approximately 2 % slope
Vegetation: Savanna grassland with scattered *P. curatellifolia* and occassional *D.cinerea.*
Parent Material: Granite
USDA Soil Classication: Ustipsamment

Description:
0-13 cm:
Dark brown (10YR 6/3 dry, 3/3 moist), dry and soft coarse sand with numerous fine roots. Weak medium to coarse subangular blocky structure; well drained and good permeability. Clear smooth boundary to:

13-33 cm:
Dark yellowish brown (10YR 5/4 dry, 4/4 moist) dry and soft coarse sand with numerous fine roots. Weak medium to coarse subangular blocky structure; well drained and good permeability. Abrupt smooth boundary to:

33-68 cm:
Stoneline, many quartz stones (< 3 cm), rapid permeability and well drained. Abrupt smooth boundary to:

68-90 cm:
Light yellowish brown (10YR 6/4 moist) gravelly, moist very friable coarse sand with faint mottles and many fine roots. Apedal structure; moderately well to moderately poorly drained with good permeability. Abrupt transition to:

90-140 cm+:
Strong brown (7.5YR 4/6 moist) moist friable soil mixed with soft weathering parent material with a few red (2.5YR 4/6 moist) mottles and few fine roots. Massive, slightly compact structure; moderately restricted permeability and moderately poorly drained.

MUKUVISI WOODLANDS PIT 1 – ANALYTICAL DATA

DEPTH	0-13 cm	13-33 cm	33-68 cm	68-90 cm
DM%	99.7	99.8	Not sampled	99.8
TEXTURE	Sand	Sand		Sand
CLAY %	4	2		2
SILT %	3	6		7
FINE SAND %	44	39		39
MEDIUM SAND %	24	30		29
COARSE SAND %	24	23		23
pH (CaCl)	4.9	4.8		5
Ex. Ca m.e.%	0.9	0.5		0.9
Ex. Mg m.e.%	0.2	0.2		0.4
Ex. Na m.e.%	0.02	0.02		0.02
Ex. K m.e.%	0.02	0.04		0.08
TEB m.e.%	1.1	0.8		1.4
CEC m.e.%	1.5	1.4		2.3
Base Saturation %	73	56		61

MUKUVISI WOODLANDS PIT 2 – PROFILE DESCRIPTION

Location: Muk-Prot experimental area
Site: Upper slope position on the catena with approximately 1-2 % slope
Vegetation: Fire protected miombo woodland, *J. globiflora* dominant near pit site, also a few *B. spiciformis*, *U. kirkiana* and *Pseudolacnostylis mapruneifolia*.
Parent Material: Granite
USDA Soil Classication: Ustipsamment

Description:

0-10 cm:
Very dark brown (10YR 4/2 dry, 2/2 moist) dry soft medium sand with a weakly developed medium to coarse subangular blocky structure and numerous fine and coarse roots. Well drained and good permeability. Clear smooth transition to:

10-30 cm:
Dark yellowish brown (10YR 6/3 dry, 4/4 moist) dry soft medium sand with a weakly developed medium to coarse subangular blocky structure and numerous very fine and few coarse roots. Well drained and good permeability. Abrupt smooth transition to:

30-50 cm:
Stoneline, many quartz stones (< 3 cm), rapid permeability and very well drained. Few fine and medium roots. Abrupt smooth boundary to:

50-100 cm+:
Variegated soft weathering parent material.

MUKUVISI WOODLANDS PIT 2 – ANALYTICAL DATA

DEPTH	0-10 cm	10-30 cm	30-50	50-100
DM%	99	99.8	Not sampled	Not sampled
TEXTURE	Sand	Sand		
CLAY %	3	3		
SILT %	7	5		
FINE SAND %	36	41		
MEDIUM SAND %	34	32		
COARSE SAND %	21	18		
pH (CaCl)	4.9	4.8		
Ex. Ca m.e.%	1.23	0.62		
Ex. Mg m.e.%	0.33	0.25		
Ex. Na m.e.%	0.05	0.03		
Ex. K m.e.%	0.16	0.03		
TEB m.e.%	1.77	0.93		
CEC m.e.%	2.14	1.4		
Base Saturation %	83	66		

MUKUVISI WOODLANDS PIT 3 – PROFILE DESCRIPTION

Location: Muk-Burn experimental area
Site: Upper slope position on the catena with approximately 1-2 % slope
Vegetation: Annualy burnt miombo woodland, *J. globiflora* dominant near pit site, also a few *B. spiciformis*, *U. kirkiana*, *Protea* spp., Vangueriopsis lanciflora, Vangueria infausta, C. molle and D. cinerea trees and shrubs.
Parent Material: Granite
USDA Soil Classication: Ustipsamment

Description:

0-10 cm:
Black (10YR 4/2 dry, 2/1 moist) dry soft medium sand with a weakly developed medium to coarse subangular blocky structure and numerous very fine roots. Well drained and good permeability. Clear smooth transition to:

10-33 cm:
Dark yellowish brown (10YR 6/3 dry, 4/4 moist) dry soft medium sand with a weakly developed medium to coarse subangular blocky structure and numerous very fine and few coarse roots. Well drained and good permeability. Abrupt smooth transition to:

33-56 cm:
Stoneline, many quartz stones (< 3 cm), rapid permeability and very well drained. Few fine roots. Abrupt smooth boundary to:

56-140 cm+:
Variegated mainly red (2.5YR 4/6 moist), yellowish brown (10YR 5/6 moist) and strong brown (7.5YR 5/8 moist) soft weathering parent material.

MUKUVISI WOODLANDS PIT 3 – ANALYTICAL DATA

DEPTH	0-10 cm	10-33 cm	33-70 cm	70-140 cm
DM%	99	99.6	Not sampled	98.9
TEXTURE	Sand	Sand		Sandy clay loam
CLAY %	2	2		21
SILT %	5	5		10
FINE SAND %	38	41		30
MEDIUM SAND %	32	29		15
COARSE SAND %	24	23		24
pH (CaCl)	4.8	4.9		4.7
Ex. Ca m.e.%	0.9	0.8		0.7
Ex. Mg m.e.%	0.6	0.4		1.2
Ex. Na m.e.%	0.03	0		0.03
Ex. K m.e.%	0.11	0.02		0.18
TEB m.e.%	1.64	1.1		2.2
CEC m.e.%	1.95	1.5		4.2
Base Saturation %	84	77		52